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US Army Research Laboratory

A Report on Army Science Planning and Strategy 2016

by Joseph N Mait

NOTICES

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by Joseph N Mait
Office of the Director, ARL

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14. ABSTRACT

Under the direction of the Assistant Secretary of the Army for Acquisition, Logistics, and Technology (ASA[ALT]), the US Army Research Laboratory (ARL) hosted a series of meetings in fall 2016 to develop a strategic vision for Army Science. Meeting topics were vetted through the ARL Director and approved by the ASA(ALT). Their selection was based on their potential to dramatically impact military capabilities in the long term. This report is a summary of those meetings and their outcomes.

The following 6 topic areas were selected: Human-Agent Teaming, Neural-Inspired Artificial Intelligence, Distributed Information Processing and Data Analytics, Materials for Sustainable and Mission Flexible Intelligent Systems, Bioenabled Materials Synthesis and Assembly, and Towards a Science of Complexity.

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Executive Summary

Under the direction of the Assistant Secretary of the Army for Acquisition, Logistics, and Technology (ASA[ALT]), the US Army Research Laboratory (ARL) hosted a series of meetings in fall 2016 to develop a strategic vision for Army Science. Meeting topics were vetted through the ARL Director and approved by the ASA(ALT). Their selection was based on their potential to dramatically impact military capabilities in the long term. This report is a summary of those meetings and their outcomes.

The following 6 topic areas were selected: Human-Agent Teaming, Neural-Inspired Artificial Intelligence, Distributed Information Processing and Data Analytics, Materials for Sustainable and Mission Flexible Intelligent Systems, Bioenabled Materials Synthesis and Assembly, and Towards a Science of Complexity. Questions considered at these meetings included the following:

- Within this technical area, what capability can it deliver to the military 25 years from now?
- What technical hurdles exist that limit our ability to realize this capability?
- What research does the Army need to support now to overcome these hurdles and enable the desired capability?

Meeting organizers were all senior members of ARL's technical staff and include ARL Branch and Division Chiefs, elected Fellows, and Army STs. For each meeting, ARL invited a small number of world-class experts as speakers, with a long-term, broad view of the specific area and an awareness of its trends. The meetings were structured to obtain a variety of viewpoints, not just near-term DOD-related expertise. Target attendance per meeting was roughly 25. Attendees spanned a large variety of Research and Development (R&D) organizations, both civilian and defense.

Based on the output of the meetings and subsequent discussions among meeting organizers, ARL developed the following specific recommendations.

ASA(ALT) should invest in the following programs:

- Support a collaborative effort across industry, academia, and the Army research community focused on modeling emergent team behaviors as a function of individual human and nonhuman members, and approaches to augment individual behaviors and functions to improve team performance.

- Support a multidisciplinary collaborative effort between the Army research community and academia that addresses combining neuroscience with artificial intelligence. Research foci include distributed artificial intelligence for tactical applications and coupling artificial intelligence to action.

- Support a multifaceted program (internal, external, and collaborative) in Adversarial and Collaborative Reasoning and Machine Learning to develop robust, friendly artificial intelligence, and penetrate, characterize, and exploit adversarial artificial intelligence. The research program must engage both social and behavioral scientists, as well as information and computational scientists.

- Support a collaborative effort between industry, academia, the Army training and doctrine community, and the Army development community to develop portable artificial intelligence capabilities ("AI in My Pocket") that enable the near-instantaneous delivery of tailored context-specific support to Soldiers in complex environments and dynamic situations ranging from situational awareness and dynamic mission planning to embedded training and readiness.

- Support a collaborative effort across industry, academia, the Army research community, and the Army analysis community to establish an analytics infrastructure that addresses standards, methods, and tools for training, testing, validation, and verification of doctrine—for example, methods and approaches to interpret and quantify Soldier and joint Soldier-intelligent systems performance for physical tasks and decision making.

- Establish an academic center to develop the science of materials integration to enable the ingestion, circulation, and metabolic transpiration of energy and power for local actuation and computation in a distributed and resilient manner.

- Support internal Army research efforts that focus on materials and subscale functional elements to promote rapid assembly and synthesis of materials across multilength scales, modeling and simulation, and fabrication technology to produce complex multimaterial, multifield metamaterials.

- Establish a collaborative effort between the Army research community and academia to develop fabrication and manufacturing processes and procedures to produce multifunctional building blocks unique to intelligent systems.

- Support an extramural program in Complexity and Emergence to develop mathematical models for predicting nonequilibrium behavior of complex multiscale systems that advance our understanding beyond statistical physics and nonlinear dynamics.
- Increase the hiring of mathematicians to enhance the capacity for mathematical analysis internal to Army laboratories.
- Support a multifaceted program (internal, external, and collaborative) in Living Materials to develop the principles enabling bioassembly and manufacturing of complex synthetic and biocomposite materials and to identify factors capable of accelerating the process to reduce maturation time.
- Support internal Army research efforts to enhance Army investments in multiscale modeling to accelerate the rate of discovery and understanding in biology by fusing multiscale modeling with bioinformatics.

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1. Introduction

In 2013, the Assistant Secretary of the Army for Acquisition, Logistics, and Technology (ASA[ALT]) charged the US Army Research Laboratory (ARL) to develop a strategic research plan for the US Army for the next 20 to 30 years. In the years since that initial request, ARL has engaged in an annual examination of capabilities that may provide the Army with an advantage in future conflicts. Integral to this examination is an assessment of the hurdles that hinder us from achieving this capability and of the latest scientific opportunities that increase the likelihood of overcoming these hurdles.

This assessment, refined each year, has helped to shape Army investments in science and technology. For example, in 2014, the report recommended increased in-house efforts in quantum information and sensing in conjunction with the establishment of an off-base lab or a joint research institute with a university. Consequently, ARL's investment in Quantum Information Science is now close to $15M and includes collaborative efforts between ARL, the US Naval Research Laboratory (NRL), the National Institute of Standards and Technology (NIST), and the University of Maryland. In 2015, the notion that, in urban terrain, the Army should "plug into the city" evolved into concepts for the Internet of Battlefield Things. In addition, "just add water protection" evolved into ARL's program on Expeditionary On-Demand Manufacturing.

This report provides the assessment and recommendations to ASA(ALT) from the meetings held in fall 2016.

2. Technical Perspective

ARL recognizes that armed conflict remains a contest of wills and that actors in conflict fundamentally seek to persuade others to accept their perspective. ARL also recognizes that, historically, investments in science and technology focused on combat in the physical domain. However, as stated in the report of the first Army Science Planning and Strategy meetings in 2014, the means for this persuasion, now and into the near future, exist in 3 realms (Fig. 1)[1]:

- physical, the domain of activities defined in space and time by the laws of physics;

[1] US Army Research Laboratory (US). A Report on Army Science Planning and Strategy [internal]. Aberdeen Proving Ground (MD): US Army Research Laboratory (US); 2014 Mar.

- informational, the domain of activities defined by thought and perception; and
- cultural (or human), the domain of activities defined by the interaction of people and societies.

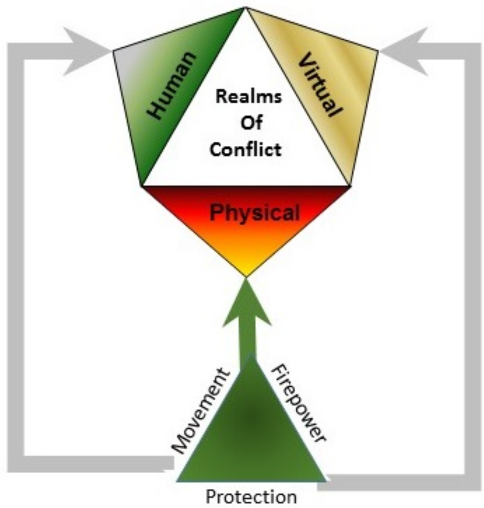

Fig. 1 Three realms of future conflict

ARL has focused its strategic intentions on these 3 realms and in recent years in overlapping areas, such as mixed teams of humans and intelligent systems, and operations in cyber space whose effects are realized in physical space.

To focus further its strategic research intent, in 2016 ARL identified several essential research areas (ERAs) critical to enabling the future Army force. ARL's ERAs are clustered in 4 groups: **Intelligent Teams**, which recognizes the importance of intelligent systems to future capabilities; **Vulnerabilities and Constraints**, which acknowledges the impact of operating intelligent systems in a contested and complex environment; **Implementation**, which addresses the integration of individual technologies to realize and apply autonomous capabilities; and **Discovery**, in which scientific opportunities drive the development of new capabilities.

Intelligent Teams: On the future battlefield, humans will interact intimately with artificially intelligent systems. Intelligent Teams considers the abstract boundary between humans and intelligent systems across which information is exchanged, increasing the intelligence of engineered systems and preparing Warfighters to engage with and exploit intelligent systems to create an effective fighting force.

Vulnerabilities and Constraints: Although new information technologies can help commanders make more informed decisions, they also present the commander with new vulnerabilities, both physical and virtual, as well as limitations.

Implementation: To ensure that the foundational advances pursued in ARL's Essential Research Areas have a path to practical application, the third cluster considers issues related to implementation.

Discovery: Discovery is the process of identifying, creating, developing, and exploiting innovative, yet Army-relevant, science and engineering advances. Discovery is essential to the Army's mission. It ensures the Army's continuing and future technological superiority, and creates technological surprise for our adversaries while avoiding technological surprise for ourselves.

All of the fall 2016 meetings address knowledge gaps evident in the ERAs. Three meetings address the Intelligent Teams cluster: Human-Agent Teaming, Neural-Inspired Artificial Intelligence, and Distributed Information Processing and Data Analytics. Under Implementation, Materials for Sustainable and Mission Flexible Intelligent Systems considered the limitations of current materials to address the needs of mobile intelligent systems.

Finally, ARL recognized that all advances in science and technology are not grounded in the physical sciences. The potential exists for biology and mathematics to enable future Army capabilities as well. However, these have not yet been demonstrated, which puts them in the realm of Discovery. The meeting Bioenabled Materials Synthesis and Assembly considered how biology can be exploited to improve the properties of nonbiological materials. The meeting Towards a Science of Complexity identified deficiencies in present analysis tools to model and predict the behavior of complex systems, both physical and virtual.

During fall 2016, ARL conducted six, 2-day meetings in these topic areas. Each meeting addressed the following questions:

- What capability can this technology deliver to the military 25 years from now?
- What technical hurdles exist that limit our ability to realize this capability?
- What research does the Army need to support now to overcome these hurdles and enable the desired capability?

The meetings were structured to obtain a variety of viewpoints, not just near-term Department of Defense (DOD-related expertise. Attendance was invitation-only, and the number of attendees per meeting was roughly 25 but varied from meeting to meeting. ARL invited a small number of world-class experts as speakers from government, academia, and industry, who have a long-term, broad view of the specific area and its trends.

The next section summarizes the discussions that occurred within each meeting. Recommendations for research in each area are indicated. The full meeting summaries are found in the Appendix.

3. Discussion

3.1 Human-Agent Teaming

The future Army mission is expected to involve high-tempo operations and engagements with near-peer adversaries across distributed, multidomain spaces that are unlike any previously encountered. Unique operational challenges that span a complex mix of physical and cyber domains, ranging from sparse rural to dense mega-city environments, will require adaptive vehicle-based Soldier-systems to possess a range of capabilities extending well beyond those expected for traditional military vehicles. Future concepts for these Soldier-systems will be influenced by future mission challenges (e.g., multicultural environments, significant increase in intelligent systems, dense urban areas), constraints and desires for specific approaches (e.g., distributed teams, reduced crew sizes, closed-hatch operations, effective Soldier-autonomy teaming), and the direction of technological advances (e.g., machine-augmented and intelligent agent–enabled task execution, adaptive and individualized Soldier-system design).

A 2015 Army Science Planning and Strategy Meeting (ASPSM) on Individualizing Technology for Effective Teaming focused on identifying research areas important to Soldier-autonomy teaming within this mission space. The group then used that perspective to derive concepts of future human-autonomy teams and highly critical future research questions. This 2016 ASPSM on Vehicle-based Soldier-Autonomy Teaming augments those results by attempting to use a different perspective to also identify future concepts of teaming and critical future research questions. Specifically, this meeting focused on future Soldier-autonomy team operations, interactions with the battlespace, and capabilities enabled through manned vehicle-based Soldier systems. The group analyzed those capabilities to derive concepts of future Soldier-autonomy teams and fundamental research required to enable their realization.

Capabilities

Future Soldier-autonomy teaming capabilities were discussed in 3 general mission contexts that were chosen to encompass a variety of operational challenges. These included a presence patrol in a low-density urban environment, leader-interaction in a rural environment, and extraction from a megacity environment. Across the discussions, a strong theme emerged that interface technologies, comprising sets of intelligent agents, hereafter referred to as intelligent crewstations, will be a critical technology to "team" with Soldiers while executing all phases of operations. Advancing technologies for intelligent crewstations will enable mission planning, execution, dynamic adjustment, and after-action review for improved training. Moreover, this foundational intelligent crewstation-Soldier team will provide an essential functional unit to enable manned vehicles to team with other manned and unmanned assets to maintain survivability and lethality during mobile operations across a range of environments. In addition to the intelligent crewstation theme, several other strong themes of future capabilities also emerged from the meeting:

- Intelligent Soldier aides for operational training, mission planning, and rehearsal
- Effective real-time maintenance and communication of situational awareness across Soldier-autonomy teams resilient to degraded, compromised, and rapidly changing informational conditions
- Situation-adaptive reasoning, dynamic resource allocation, and task management to support collaborative Solider-autonomy decision making and performance
- Context and state-aware autonomy to detect or anticipate operational needs and take necessary actions to support the Soldier-squad mission
- Heterogeneous unit teaming, including direct interactions across mounted, dismounted, and unmanned assets that function robustly across the information and capability divides between platform-specific mounted and dismounted technologies.

Fundamental Research

Fundamental research was identified that will be required to enable the realization of future Soldier-autonomy team capabilities. Several of the most critical research questions cut across major capability themes identified previously:

Human State Characterization: There is a need for characterizing the human state (cognitive/affective/social) in ways that are useful to and usable by (i.e., that can be reasoned about) autonomy and other humans to facilitate mutually adaptive teams. Underlying this general requirement are research needs that include understanding variability across and within humans; understanding the limits and the opportunities for new mathematical methods to address real-world levels of complexity with potentially unstructured and incompletely characterized state space; and understanding the relationships between sensing (i.e., characteristics and performance properties under operational conditions) and human state estimation biases and variability across multiple modalities and scales.

- Recommendation: Human State Characterization is directly in line with the research into “Estimating and Predicting Individual Soldier Capabilities, States and Behaviors” identified by the 2015 Individualizing Technology for Effective Teaming ASPSM. This area presents an enormous, pervasive challenge that is critical to a wide range of military and nonmilitary capabilities. The Army recently reprioritized significant internal and external fundamental research efforts (starting FY17) that are capitalizing on recent technological breakthroughs to enable significant progress in this area. The Army’s large collaborative effort across industry, academia, and the government should be continued.

Enhanced Communication between Humans and Machines: There is a need to develop better approaches to exploit human multisensory capabilities and share concepts for effective communications between humans and machines. Underlying this requirement are research needs including cross-modal approaches to enabling real-time human comprehension under constraints of bandwidth, information quality, and task; predicting the effects of individual Soldier variability in sensory perception and utilization, as well as the effects of variability arising from operational/technological factors (i.e., clothing, headsets, crewstations) on the ability to comprehend information; and developing approaches to share concepts across the information and capability divides of platform specific manned, unmanned, and dismount technologies.

- Recommendation: This area presents basic and applied research challenges critical to Soldier-autonomy and Soldier-Soldier teams. The Army has small-to-moderate funding related to fringes of this research area. Advances related to natural language processing, advanced computational approaches, and novel interface technologies may enable breakthroughs in effective communications. With additional resources, the Army has the opportunity to make fundamental advancements on the critical issue of sharing concepts across the information and capability divides of platform-specific manned, unmanned, and dismount technologies.

Linking Individuals to Team Behavior: There is a need to understand the mutual influence and adaptations between individual and team behavior. How does an individual impact team behavior and how does team behavior impact the individual? Teaming is not about boxes and functionality, it is about interdependence among the boxes. Accounting for interdependence requires observability, predictability, and directability. Perception and adaptability provide feedback among these 3 elements and define research requirements that include developing the interface between observability and predictability; understanding how a transaction between humans and intelligent systems occurs; developing tools that help identify parameters critical in collaborative behavior; developing tools to understand the psycho-physiology of intelligent systems and hybrid teams; and developing meaningful measures to assess team behavior.

- Recommendation: Linking Individuals to Team Behavior is directly in line with the research into “Linking Individuals to Emergent Team Behavior” identified by the 2015 Individualizing Technology for Effective Teaming ASPSM. This area presents an emerging challenge as autonomy increases in intelligence and capability. The Army currently has insufficient fundamental resources dedicated to this area. Addressing this challenge, the Army needs additional resources to begin a large collaborative effort across industry, academia, and the government focused on modeling emergent team behaviors as a function of individual human and nonhuman members, and approaches to augment individual behaviors and functions to improve team performance.

Robust Human-Autonomy Integration: There is a need to understand approaches to match human capabilities with the capabilities of rapidly advancing autonomies. Underlying this general requirement are research needs that include identifying the critical attributes of agents that would successfully integrate in the crew-automation environment; understanding human-autonomy integration in terms of recruitment and assembly of teams; understanding how to establish training protocols and potential removal from service or prevention of inclusion; developing novel approaches to integrating humans and autonomy focusing on nontraditional tasking and decision-making processes; devising principles to develop an adaptable user interface to facilitate tuning to individual variability (biases, proclivities, capabilities) and principles and ethics underlying the generation, evaluation, and refinement of adequate mission plans for distributed human-autonomy teams. There is a need to define the kind of assumptions that can and should be made considering long-term societal shifts in the relationship between humans and automations, taking into account anticipated perfusion of sensor, computational, and control technologies throughout daily life.

- Recommendation: Robust Human-Autonomy Integration is consistent with themes within the research into “Enabling Joint Human-Technology Team Capabilities and Performance” identified by the 2015 Individualizing Technology for Effective Teaming ASPSM. This area presents an emerging challenge as autonomy increases in intelligence and capability. The Army currently has insufficient fundamental resources directly dedicated to this area but has unique capabilities necessary to address this challenge. To do so, the Army needs additional fundamental resources focused on robust human-autonomy collaborative decision making and functionality, as well as fundamental and applied resources in intelligent crewstation technologies.

Human-Autonomy Teaming Analysis: There is a need to develop the requirements for tools to help design and build human-machine systems. We have tools to analyze automation, and we have tools to analyze human performance; however, analyzing teams of humans and intelligent systems is not a linear combination of these 2 and the current methods and approaches to analyzing heterogeneous teams of humans and autonomous agents remain deficient. Underlying this requirement are research needs that include developing system engineering practice and models to 1) better integrate the human; 2) account for dynamics of work, team, individuals, and environment; 3) better account for the concept of time; 4) present alternatives critically; and 5) account for intelligent systems working collaboratively with humans. Further sufficient optimality criteria need to be defined and implemented with appropriate metrics for human-autonomy team success.

- Recommendation: Human-Autonomy Teaming Analysis presents basic and applied research challenges critical to all stages of technology development from early concepts to test and evaluation. The Army has minimal funding targeting the advancement of human-autonomy team analysis methods and approaches. To address this critical emerging challenge area, the Army needs addition fundamental and early applied investment in advancing real-time, human-in-the-loop methods and approaches to interpreting Soldier and joint Soldier-autonomy performance, as well as novel approaches to collaboratively integrating intelligent analysis technologies with human subject matter expertise.

3.2 Distributed Information Processing and Data Analytics

The proliferation of distributed big data requires radical rethinking of the US Army’s approaches and technologies for intelligence gathering, processing, and analysis. Rapidly growing volumes of data are gathered by military assets, nonmilitary sensors everywhere (e.g., security cameras, mobile phones), the Internet of Things, and social media sites pose new technical and operational challenges, threats, and opportunities for the Army. The volume, diversity, density, velocity, mobility, and distribution of the data will be potentially multiple orders of magnitude greater than in today's world. Considering the recent re-emergence of artificial intelligence (AI), especially the successes in Machine Learning, the Army finds itself at a scientific inflection point for the development of game-changing capabilities, as reflected in the findings to follow.

Adversarial and collaborative reasoning and machine learning require advances in ways to penetrate and characterize an enemy's AI systems, to exploit enemy AI, and to improve and protect friendly AI. Important scientific problems yet to be solved in this space include the ability for one AI system to learn from another; the ability for an AI to validate that another AI is behaving as expected and not working outside its parameters, or maliciously; and the ability for an AI to move without detection for stealth penetration and learning. Research in these topics may focus on cyber and electromagnetic warfare, and will require serious attention to study of realistic adversarial activities and sophisticated red teaming.

Avoiding vulnerability to adversarial deceptions will be particularly important in ill-structured problems typical of military environments. These environments are characterized by complexity, emergent and inconsistent behaviors, ambiguous cause and effect, and highly dynamic environments and behaviors. New approaches are needed to make machine learning and reasoning more resilient and resistant to deception, false facts, biases, and influences. It might be possible that exploiting the anticipated high degree of connectivity on a future battlefield, heavily saturated with sensors and intelligent machines/munitions, will provide opportunities for cross-validation of facts and inferences. This area of research is likely to be closely coupled with the one mentioned previously, with related requirements.

Machine reasoning in effective interaction with humans (users, developers, maintainers, etc.) is critical for military environments. However, phenomena in human-machine systems are notoriously difficult to understand, predict, and mitigate. Approaches are needed to ensure that conclusions, indicators, and warnings provided by intelligent data processors are consistent with human decision-making needs and are not counterproductive with respect to human cognitive processes. Novel methods for validation and verification will need to emerge to ensure adequate quality of operations by such complex human-machine systems. A long-term research effort, as a close collaboration of Army and academia scientists, is likely to be required to make significant progress in this area.

Exploitation of open-source intelligence (OSINT) and nontraditional sources are critical as the amount of easily accessible, military-relevant information has grown exponentially with the proliferation of social media sites and applications. Traditional OSINT sources include, but are not limited to the following: social media, news sources, mass transit maps and schedules, and the dark web. Nontraditional OSINT sources can include data about power usage, emergency responders, and hospital activity; cameras; traffic patterns; and mobile phone usage. Approaches are needed to accurately identify the signal amongst the noise in the massive amount of information and data fusion to intelligently bring together various sources and types of data, as well as to combine OSINT with human intelligence (HUMINT) and other intelligence information. A research program in this area should consider lessons learned in recent efforts in soft-hard fusion.

Recognizing emergent phenomenon and pattern of life sooner than human analysts is seen as especially important when dense urban areas or megacities become the operational environment. Analysts and Soldiers are increasingly dealing with ill-structured, highly unpredictable problems having 1) emergent behaviors and 2) complex relationships with freedom of action and interaction, ambiguous cause and effect, inconsistent behavior, and uncertainty. Current methods of intelligence analysis are unlikely to be effective. It is hypothesized that machine learning approaches, algorithms, and systems can help make sense of complex situations, recognize emergent phenomenon faster than any single or group of analysts/Soldiers could, objectively explore a greater number of hypotheses, many of which might have escaped human attention, and overcome confirmation bias. A research program in this area must address collecting large volumes of highly diverse, yet militarily relevant, data and to engage social and behavioral scientists.

Ensuring analysts trust in how data are collected, entered, stored, accessed, and analyzed in the system requires a range of new approaches. Data must be vetted with regard to its accuracy. Systems must be able to maintain provenance information such that analysts can always trace information to its source, determine who entered it into the system, and see who accessed it along the way. Trust will be developed through the consistent demonstration and improvement of the effective exploitation of these data. Examples of such exploitations will include the use of social network analysis for social influence prediction and prevention; on-the-fly machine learning capabilities to develop common ground and ad hoc questioning; and especially, moving from analysis of past events to prediction. While ARL has a strong portfolio of trust-related research, it is a challenging area where progress will require time.

Portable artificial intelligence capabilities (AI in My Pocket) seems enabled by the dramatic and continuing increase in digital data generated from sensors (physical, electronic, and social) combined with a growth in computing power (both realized and on the near horizon). Such systems could provide Soldiers with near-instantaneous knowledge to make near-immediate sense of complex environments and situations. Research must be performed on approaches by which AI can replicate, complement, and improve the human brain for information processing, sense-making, and decision-making for military-relevant problems. Successful research efforts will require close partnering with academia and the Army training, doctrine, and experimentation community.

Infrastructure, methods, standards, and tools are necessary to make advanced analytics rapid, reflective, and deployable. Flexible infrastructure environments with sufficient diversity are needed to accommodate a variety of applications, domains, and users. Challenges include 1) standardization of data and ground truths, analytic algorithms, software tools, performance metrics, and validations; 2) physical infrastructure that scales in terms of processing/computer power and classification levels; 3) operating infrastructure in terms of format/primitives, training, and testing environment (batch or streaming); and 4) validation and verification of Concept of Operations (CONOPS)/doctrines at different classification levels on adaptive learning and evolving complex systems. Partnering with industry and the Army experimentation community will be critical to successful research in these areas.

3.3 Neural-Inspired Artificial Intelligence

Technologies in AI have the potential for significant Army payoff. Advances in neuroscience are leading to understanding of neural structure, function, and networking, providing new insights into the functional components of intelligence and how they interact. Focusing AI research on key Army issues will leverage commercial advances and accelerate system development. This meeting brought together a unique mix of research leaders in neuroscience, brain modeling, vision, artificial neural networks, AI, cognitive computing, and circuits to identify critical research areas.

Several critical Army aspects of AI are unlikely to be addressed by any commercial enterprise. Unlike commercial applications, tactical military applications are reliant on heterogeneous architectures across Army platforms, networks, sensors, and processors. Distributed operation is essential and must be resilient to attack, mobility, and network failure. Architectures need to be engineered to enable modularity and composability, incorporate autonomous agents, and human interaction. They need to be linked with control and learning to enable active attention and problem solution in time-critical scenarios, and readily embedded into applications. They cannot be reliant on massive supervised training data sets but instead must incorporate prior knowledge.

A key finding for the long term is the need for a *multi-disciplinary combination of neuroscience and AI.* There is a separation between computational neuroscience (brain modeling) and AI, with relatively little research overlap. *Multi-disciplinary research should be enhanced, benefiting both Army AI and brain research.*

Army AI research should 1) focus on distributed AI for tactical application and 2) couple AI and action. 1) Distributed intelligence is not a current research emphasis in the AI research community, although some limited aspects might emerge commercially due to dense internetworking. Distributed intelligence is critical to Army applications and should be coupled with cognitive networking to provide resilient AI systems. Neuroscience is leading to understanding of neural structure, function, and networking within the brain, providing new insights into the functional components of intelligence and how they interact. Mathematical modeling is needed for this often empirically based area. 2) Active perception, focus of attention, motor control, and other cognitive programs are evident in neuroscience. These techniques should be explored for the combination of AI and robotic autonomy in dynamic Army settings (e.g., in task-based models). There are large fundamental gaps in understanding the use of memory and attention in AI. Recent neuroscience has demonstrated focus of attention mechanisms, for example, in vision. Long-term multidisciplinary study is needed to develop the science and practice of action-oriented AI.

Beyond human sensing, AI should be applied to Army sensor fusion and processing. The recent success of artificial neural networks (ANNs) has demonstrated early progress in fusion of speech and vision. These techniques should be expanded upon and applied to Army problems (e.g., the fusion of electronic warfare, IR, and active sensing). Long-term research issues include fusion over different sensing and time scales, and coupling with action-oriented AI to enable autonomous mobile sensing platforms.

A fundamental new science of Soldier-AI interaction is needed. Human-machine teaming is largely heuristic, and theoretical underpinnings are needed to develop systematic design methods. Psychological insight, mathematical modeling, and systems engineering must be combined and not left to separate research avenues. The science of interaction should encompass multimodality, including speech, vision, gestures, virtual reality, and brain-computer interfaces with wearable sensors such as electroencephalogram (EEG). AI designs must incorporate the ability to query humans in 2-way dialog for learning, understanding, and task-oriented teaming.

AI architectures are critical and fundamental design principles are lacking. Some key issues include the following. 1) Data abstractions and representations can determine the success of AI; however, this is an insufficient understanding and theoretical underpinning for this problem. 2) Incorporating prior knowledge is key to reduced training cycles and unsupervised learning. The limitations of big-data supervised training are now apparent and pose significant barriers to applying AI in Army scenarios. 3) Active learning is needed over different time scales with adaptive cost functions. Neuroscience demonstrates that learning is continuous and adapts and changes focus over time. A fundamental science of learning is needed that leads to algorithms capable of these more general learning attributes, coupling with control to enable active learning. 4) AI and memory should be coinvestigated. Human memory appears to be massively distributed, providing resilience and robustness. Long-term memory consolidation in humans appears to be a slow process, whose understanding is likely to provide new insights into AI architectures and processing. Neuroscience studies and knowledge bases should be coinvestigated to advance fundamental understanding and provide new memory architectures and algorithms, with tight coupling to active learning and distributed AI. 5) Links are needed between empirical ANN architectures and theoretical AI designs. Work in layered representations should be accelerated to provide systematic design principles and direct match with applications. 6) Circuit architectures are fundamental. Size, weight, and power (SWAP) constraints and reliance on wireless networks will continue to frame the achievable AI for Army scenarios. While commercial success of AI will drive circuit development for mobile applications, it is incumbent on the Army to discover canonical architectures that provide modularity and to move AI to embedded applications. It is also important to consider going beyond the classic von Neumann computing paradigm. 7) Data collection will continue to be important to support appropriate experiments in the long term. As AI systems emerge, they will become increasingly complex and multiplatform, creating challenges for large-scale experiments, including the need for costly research infrastructure.

Army AI R&D would strongly benefit from a collaborative research alliance (CRA) or similar program with the above focus. Currently, in-house efforts largely consist of applying emerging AI tools in several disparate disciplines (e.g., autonomy, training, human-machine interaction) but are not broadly focused on long-term Army-relevant basic research in AI. Emphasis should be placed on the combinations of sciences needed, that go well beyond current collaborations. The merger of neuroscience, engineering, and computer science should be fostered and may require new in-house organizational elements. Links with autonomy, intelligent agents, and robotics will bring leap-ahead potential to already strong in-house efforts. While a focus on tactical application is recommended, large-scale intelligence should also be explored in the context of distributed high-performance computing to bring in-house efforts up to the state of the art and beyond. A CRA will provide synergy and unification for the long term, enable government personnel development in this rapidly evolving area, and accelerate the application of AI technology to specific Army problems.

3.4 Materials for Sustainable and Mission-Flexible Intelligent Systems

We hypothesize that integrated innovation in materials, synthesis, and energy has a fundamental role to play in disruptively advancing desirable and necessary intelligent platform capabilities and behaviors over a range of moderate-to-extreme operating conditions. However, this hypothesis also maintains that advances in "classical" materials, synthesis, and energy may not be sufficiently capable of expanding beyond their own inherent limitations without new and meaningful connectivity to other—perhaps disparate—physics, chemistry, biology, and computation phenomena.

Every meeting invitee was a noted pioneer in fields and activities related directly and indirectly to the meeting; indeed, it was the significance of their professional accomplishments to date that made them especially critical to helping define where the current gaps—and opportunities—lay in this area. The goal of this meeting was to create a conversation that would allow for materials, synthesis, and energy to be discussed explicitly and simultaneously in the unique context of intelligent systems. Mass, volume, and energy-efficient bounds defined the fertile space for identifying the knowledge gaps and transdiscipline work that needs to be done so that offsets in intelligent platform performance could be ensured deep into the Army's future.

The overarching conclusion was that, indeed, the potential performance benefits of intelligent systems and robotic devices are limited by a lack of comprehensive innovation and invention that more fundamentally addresses the *scale-appropriate energy, power, and materials* needs of these systems to deliver desired bulk responses, behaviors, and capabilities. There were many interesting and relevant research areas and thrusts identified with varying degrees of fidelity, and an attempt has been made to digest these into 5 key recommendations:

Material and Energy Intelligence in Robotic and Autonomous Systems

The Army needs to invest in the science of *scale-appropriate* energy and power strategies unique to intelligent systems. The ASPSM participants consistently identified physical constraints associated with current energy and power approaches as a critical limitation on intelligent system performance and potential. A holistic, comprehensive, and more deeply integrated approach to energy is recommended and would include new research for enabling intelligent management, generation, harvesting, storage, conversion, and distributed use of energy and power. This includes introducing unprecedented levels of adaptivity so the intelligent system can develop new symbiotic and other types of energy acquisition relationships (e.g., foraging of natural and manmade materials, ambient energy harvesting) within its operating environment. It would also include the need for new concepts for materials and processes that could contain the reactive materials necessary for self-sustainment (e.g., flexible materials to contain micro-combustion, catalyst materials for synthetic metabolism to generate and consume energy-dense stored chemicals, and modes of planned material and structural degradation to enable "self-cannibalism" for extending operation under critical conditions). Research investment in these new concepts provides the underpinning science foundation for potential agent-agent teaming of different scale intelligent systems to improve mission endurance, durability, and environmental adaptability.

Disrupt the Notion of an Intelligent System as a "Fixed Platform"

The confluence of materials, synthesis, energy, sensing, and computation could provide breakthrough approaches to address current limitations to intelligent system performance, maneuver, adaptivity, endurance, and resilience. Materials and subscale functional elements could be designed to promote rapid assembly and synthesis of materials across multilength scales, including materials that can be rapidly disassembled and decomposed so they can be repurposed based on the global and evolving needs and task demands of the intelligent system. In addition, new research is advocated to provide the intelligent system the low-power ability to *create and deploy tools* to better perform its assigned tasks and enable its own self-sustainment for significant gains in operational endurance. Therefore, the Army needs to invest in materials research for reconfigurable electronics and materials, distributed actuation with localized power, and computationally driven point-of-need tool synthesis informed by task requirements and environmental constraints.

Aggressively Pursue Research into Multifield Metamaterials

In recent years there have been burgeoning metamaterial demonstrations, with significant successes in complex custom electromagnetic materials for optics and antennas, and early demonstrations of passive mechanical metamaterials. Advances in microfabrication, synthesis, and additive manufacturing have matured to where we can start to realize complex multimaterial structures. This, combined with continued progress in simulation and reduced cost computation, means it is an opportune time to pursue research in multifield metamaterials with the goal of achieving novel materials that move us far beyond the limitations of traditional materials. For example, realizing scalable, tunable, highly efficient actuators supporting complex articulation, with potential for integrated sense and control, as well as materials for novel platform frames, with unique mechanical, optical, and electromagnetic properties. The successful realization of these broad potential materials will revolutionize autonomous platform design, performance, and endurance, for example, by enabling novel high-density energy sources to directly drive actuation. In addition, these materials have the potential to advance broader Army system performance included in the Cyber-Electromagnetic Activities (CEMA) communications and platform arenas.

Cyber Synthesis for Making Good on the Promises of Multifunctionality, Bioinspiration, and Point-of-Use Adaptivity

Currently, synthesis and fabrication technologies fail to enable much richer and resilient multiscale material functionality and contiguous, defect-free morphologies and subscale structures. Such processes also fail at achieving more efficient materials interfacing for discrete device/component integration. Therefore, the Army needs to invest in exquisite manufacturing of small building blocks and infrastructure with multifunctionality and point-of-use adaptivity unique to intelligent systems. For example, fundamental advances in synthesis could fully enable the benefits of a "circulatory system" to support distribution of alternative high-density energy and complex processing of energy at the location of consumption. The goal of this investment is to enable energy, power, actuation, and computation resource elements synthesis in a more distributed and resilient manner as needed in the global intelligent system. The benefits of such an investment would provide the scientific basis for informing the development of synthesis and fabrication methodologies to enable far more complex and energy-efficient robotic and intelligent system capabilities, responses, and behaviors.

Pioneering Opportunities for Computation and Modeling in Intelligent Systems

New modes of embedded computation and sensing will be equally critical to enriching the potential of material and energy performance in intelligent systems. Recent and disruptive advances in theoretical and computational material and energy frameworks, including "materials by design", and materials that can provide logic functions and sensing can enable "state machines" and disruptively shrink the response time and enable efficient new behaviors for maneuver and actuation by distributing control within the materials themselves. Similarly, advancing the development of AI as a tool to assess constraints and stretch the solution space for intelligent system design of materials, structures, processes, and energy and power cycles could enable leap-ahead performance gains in mass, volume, and energy efficiencies.

3.5 Bioenabled Materials Synthesis and Assembly

Recent advances in systems and synthetic biology, the associated high throughput screening methods, and genetic editing tools have allowed for holistic engineering of biology. Further, biological systems inherently produce spatially designated assemblies of complex hierarchical structures with extreme precision and have living material characteristics such as re-healing, adaptability, and dynamic, programmable properties. The meeting on Bioenabled Materials Synthesis and Assembly explored the fundamental questions and anticipated tools to command and control biology to achieve new materials and disruptive capabilities for the Army that are not available through traditional synthetic and processing methods, such as accessing material states not at thermodynamic equilibrium; multimaterial hierarchical assemblies with precise chemistry and architecture at the atomistic and molecular scales; and materials that dynamically respond to stimuli or changing conditions. Particular consideration was made for robustness of biological machinery and living products under nonaqueous and extreme conditions. Several capabilities were identified that may be enabled by biological approaches to synthesis and assembly. Understanding the biotic-abiotic interface and controlled assembly, disassembly, and reassembly could enable a very wide array of new, tunable, and responsive functionality and architectures.

Utilizing a dynamic and interactive meeting format, several promising research opportunities were identified, down-selected, and further explored through an evolving series of small group discussions. The opportunities are discussed in the following paragraphs.

Design, Storage, and Implementation of Instructions for Materials Synthesis and Assembly

Managing instructions for the synthesis and assembly process is a significant challenge and offers numerous opportunities for new research. A compelling desired capability is spatial and temporal control over assembly of the material architecture, which might include tracking the process via feedback in real time and using active control to steer it to a desired outcome. This is an intriguing goal that may demand synthetic methods and/or target materials that are stimuli responsive, reconfigurable, and switchable. Materials that are dynamic as part of their properties (e.g., exhibiting multiple metastable states or dynamic equilibrium) might further enable reorganization after a material is formed. For self-regulating synthetic systems, there is a need to tune equilibrium end-state for a continuum of products. A more passive approach is to provide cells the consolidated instructions for complete synthesis and assembly. There is much emphasis currently on top-level regulation with the opportunity to better develop control or modification of the proximal synthesis pathways. A worthwhile but challenging goal is breaking down hierarchical levels of cell function to manageable subunits to be used as “subroutines” for existing systems. Programmable control over active subunits may then be used to create designer materials. Self-organizing strategies are needed for complex/multicomponent systems, including self-assembly and self-repair of physical architecture and specified function across multiple scales. Programmed synthesis of intrinsically nondesignable systems is a particular challenge that highlights a theory gap—in particular, the inverse computational methods required to extrapolate from a targeted end-point back to the genetic origin and then generate the forward instructions for synthesis. Innovative strategies must also be considered to encode out-of-equilibrium higher organization and function.

Robustness to Extreme Conditions Including pH, Temperature, Unstable Nutrient Supply and/or Nonaqueous Environments

Living systems and their subcomponents are typically not robust to “extreme” environmental conditions such as temperature, pressure, and pH. Extending the operational range is a big challenge. Several ideas were considered, such as developing support systems that address specific challenges including biotic/abiotic vasculature that deliver nutrients and exoskeletons that shield the sensitive components from heat, pressure, or other stresses. Engineering biosystems for robustness was considered the most practical approach at this time. We may take advantage of the inherent adaptability of biological materials that enable survival under hostile conditions—for example, to adapt to changing energy sources (organism-level adaptation) or to develop antibiotic resistance (community-level adaptation). Four fundamental categories of engineerable biological materials and specific pathways to engineering were discussed. Bioorganisms such as bacteria and yeast have highly efficient metabolic processes that enable low-energy operation and limited waste, and evolutionary adaptability to new conditions or to develop new capabilities including operation under extreme environments. Biomachineries such as mitochondria have scalable, fast, energy-efficient synthetic processes with high fidelity and error correction, and the ability to be abiotic, multienzyme, and cell-free. Biomacromolecules such as proteins and nucleic acids have native hierarchical structures, dynamic operation, and the ability to synthesize materials with high precision, selectivity, and multifunction. Biotic-abiotic hybrids are a more complex approach with challenges involving multicomponent interactions at various length scales that may be addressed through multiscale modeling and bioinformatics.

Autonomous Sensing, Learning, and Evolving of Integrated Functions and Architecture

Biological systems have an advantage over a synthetic assembly of materials in that they can respond to a huge range of stimuli, including physical/mechanical, chemical, optical, and electrical. However, controlled use of living materials requires new paradigms for instructing individual cells and their subcomponents as well as for organizing cells across wider morphologies. Coordination of multicellular systems in particular will require a greater understanding and control over signaling and communication. Biogeneration of nonliving products has the opportunity to address non-natural materials that cannot be synthesized through other methods. Directed evolution in particular has significant potential to address complex problems for which current chemistry and materials science approaches are inadequate, such as high-performance adhesives. Significant effort will be required to identify appropriate and potentially complex selection pressures to produce integrated functional and architectural properties. Integrated computational approaches should be included to accelerate learning and success. Biogeneration of materials with living biology included has the opportunity to more actively incorporate living characteristics in the product, such as sense and response, self-healing, and continually evolving properties. Research is needed to better understand mechanisms regarding inheritance of properties as well as how the living components can be controlled to be responsive or noninteractive on demand. Providing dynamically responsive or latent activity of the living component may enable environmental robustness and have unique application value.

Army Impact and Path Forward

Bioenabled materials synthesis and assembly have the potential to provide access to sequence- and morphology-defined synthetic materials, with control from the micro- to molecular level. This unprecedented control may enable new concepts in structural and functional material design, and new modes to mitigate damage or failure. Suggested research topics that support the Army mission include the following:

- Biomanufacturing Science and Rapid Engineering: Nature extensively uses biology to manufacture complex 3-dimensional structures of different shapes, sizes, properties, and functionality; however, this is a slow phenomenon that can take years to complete a given object. This research will develop an understanding of the principles that allow bioassembly and manufacturing of natural objects and identifying factors that could controllably accelerate the process to reduce maturation time.

- Understanding the Biotic-Abiotic Interface: Fundamental theoretical and experimental studies to understand the interaction (bonding, adhesion, electron, and charge transfer) between biotic and abiotic materials. Knowledge gained from this research will impact all bioenabled research.

- Bioenabled Structures for Harvest, Conversion, and Storage of Energy: This research will focus on assembling materials that can absorb sunlight or ambient chemicals, including waste, to produce and store energy parallel to natural photosynthetic and chemosynthetic processes.

- Bioenabled Materials for Material Conversion: This research incorporates advanced recycling concepts to develop and couple biodegradation and biomanufacturing processes to convert natural resources and discarded synthetic materials to new products.

- Bioenabled Materials for Signature Management: This research will focus on photo-, thermal-, and pressure-sensitive materials for real-time control over visibility, including Time-to-Live.

- Bioenabled Information Sensing, Recording, Storage, and Retrieval: This research will use biological materials to generate, store, and communicate complex nonlinear data.

There is considerable external investment in the rapidly developing field of biosynthesis, but the skills, expertise, and equipment required to carry out this work is typically unique, making it difficult for personnel from other disciplines to effectively collaborate with and leverage those efforts. One of the gaps highlighted by the workshop attendees was the need for better communication between biologists, who better understand the capabilities available, and materials scientists, who better understand how to anticipate and meet application needs. One recommendation was for a series of workshops uniting these communities to increase exposure of cross-disciplinary opportunities and to resolve the biotic-abiotic language gap and different expectations of research timelines. These workshops may also help resolve how best to establish collaborative centers between the Army and other institutions.

Additional resources will also need to address the research gaps to enable the opportunities in this field. Gaps specific to biology include reconciling the critical role of water in biological systems with engineered synthetic material systems, methods to stimulate forced adaptation and select successful candidates to achieve high-performance materials, and a library of primitive programmable biological subroutines and inverse computational strategies to achieve complex structure and function in inherently nondesignable systems. These needs will require significant effort, and as they apply to Army applications, they may best be met by investing in a critical mass of internal experts that can appropriately steer and leverage external efforts through collaboration and transition. There are also broad, underlying gaps that do not require specific expertise in biological materials but are just as critical. Primary among them are the need for fusing multiscale modeling with bioinformatics to accelerate the rate of discovery and understanding, and the need for characterization tools that address biological scales, environments, and material types with the resolution to probe interfacial interactions. The Army has established expertise in multiscale modeling and characterization that may be grown and tuned to the biological issues presented here to provide leadership in the field toward solving Army-relevant problems.

3.6 Towards a Science of Complexity

A new way of thinking is made necessary by the demands of contemporary science to overcome the complexity barriers to modeling complex systems in multiple scientific disciplines across the Army. For example, nondifferentiability of turbulent fluid flows, unpredictable transitions of peaceful demonstrations into riots, intermittent instability of decision making induced by physiological and psychological factors (i.e., emotion), inability to predict the behavior of large heterogeneous socio-technical systems, the catastrophic cascades of failure modes on power grids, computer networks, and so on. Complexity entails the qualitative, as well as the quantitative, richness of phenomena—a delicate balance between regularity and randomness in the nonlinear dynamics.

As a community, we know how to deal with algorithmic complexity, but an algorithm assumes that a problem formulation exists, which in turn means that a mathematical model exists. Today's networks and systems are so complex that we do not have adequate mathematical tools to represent them, or even to talk about the complexity of representation. We need advances in mathematics to deal with this. Things are fairly simple if the world is heterogeneous, but well-mixed, and if we are primarily interested in steady-states. Often we do not have good spatial or temporal mixing, and even more frequently we are interested in transients (because external events occur before a steady state can be achieved). According to physicist Stephen Hawking, the 21st century will be the century of complexity.[2]

The goal of the meeting was to identify fundamental research issues that may enable future military-relevant capabilities and need to be addressed. Participants were asked to identify gaps in scientific understanding and describe how to apply existing scientific understanding to establish bounds on performance.

The following questions provided a focus to initiate discussion:

- What are the emerging mathematical, statistical, and methodological advances entailed by complexity? Assess and validate their suitability to perform complex adaptive analysis of scale-free dynamical systems in extreme hostile stochastic environments.
- What are the fundamental algorithms and models needed to create autonomous systems that can characterize, detect, adapt to adversarial behaviors, and self-heal systems in a heterogeneous networked environment to enable effective situational awareness?
- How do we measure, model, and predict the complex nonlinear dynamics of adjustment, adaptation, and intergroup levels that lead to emergent structure, culture, and physical processes (development of adversarial and allied groups, sociocultural conflict, emergent states, critical phase transition, etc.), which involves large-scale collectives, including organizations, crowds, societies, and cross-cultural relations that are critical to strategic planning and Army operations?
- How can automated robust design, discovery, and decision be achieved through advances in optimal information exchange machine-learning/

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[2] Hawking S.'Unified theory' is getting closer, Hawking predicts. Interview in San Jose Mercury News; 2000 Jan 23; 29A.

surrogate modeling, combined with physics, big data, uncertainty quantification, and optimal verification and validation?

The mathematics that scientists employ does more than simply provide models of phenomena they seek to understand. It provides the language and logical tools necessary to think about those things in a way that enables them to make new and important predictions that can be experimentally tested. To “win in a complex world”, the Army must tackle problems wherein objectives and constraints evolve in unpredictable ways. Complexity arises from the increasing heterogeneity, connectivity, scale, dynamics, functionality, and interdependence of networked elements, from the increasing velocity and momentum of human interactions and information. Increasing integration of knowledge across disciplines requires a systems approach rather than a reductionist one.

Consequently, the complexity of the connectedness problems being addressed by today’s society and Army challenges existing mathematics. To understand complexity science, mathematics must go beyond the analysis of analytic functions, not just in physics, but in the social, ecological, and life sciences as well. Fractional calculus is one way to frame the research hurdles entailed by complexity. Other approaches discussed include homotopy type theory (which combines algebraic topology, category theory, and logic), network and graph mathematics, as well as renormalization group theory.

Based on conclusions drawn within the workshop, many of which overlap with those reached by the ARL’s ERA Gap analysis, we recommend the Army support internal, external, and collaborative programs in Complexity and Emergence to address the following 3 areas of critical need:

Predicting Nonequilibrium Behavior

- A mathematical definition of complexity and its quantification are lacking.
- There is critical demand for mathematical models of finite size, far-from-equilibrium, complex multiscale systems, beyond statistical physics, and nonlinear dynamics.

Lack of Physical Principles

- We do not understand how the emergent dynamics and intelligence of heterogeneous collectives respond to externally imposed gradients or current densities.
- Need to quantify sources and control of uncertainty and failures in complex systems.

Control of Information Exchange

- Require theory for how information exchange controls automated robust design, discovery, and decisions that include big data, uncertainty quantification, failure, and optimal verification and validation.

4. Recommendations

Much of the discussion held at the meetings focused on the melding of dissimilar entities—for example, teams of humans and intelligent systems, biotic and abiotic materials, bulk materials, and functional materials. The recommendations that follow emphasize the need to address knowledge gaps that exist at the overlap between the different areas. These recommendations highlight a specific gap and also identify communities that should be involved in addressing the gap. Further, given the complexity of such heterogeneous systems, discussion across the meetings underscored the need for new analytic techniques to understand and predict the behavior of such systems.

Intelligent Teams

- Support a collaborative effort across industry, academia, and the Army research community focused on modeling emergent team behaviors as a function of individual human and nonhuman members, and approaches to augment individual behaviors and functions to improve team performance.
- Support a multidisciplinary collaborative effort between the Army research community and academia that addresses combining neuroscience with AI. Research foci include distributed AI for tactical applications and coupling AI to action.
- Support a multifaceted program (internal, external, and collaborative) in Adversarial and Collaborative Reasoning and Machine Learning to develop robust, friendly AI, and penetrate, characterize, and exploit adversarial AI. The research program must engage both social and behavioral scientists, as well as information and computational scientists.
- Support a collaborative effort between industry, academia, the Army training and doctrine community, and the Army development community to develop portable AI capabilities ("AI in My Pocket") that enable the near-instantaneous delivery of tailored context-specific support to Soldiers in complex environments and dynamic situations ranging from situational awareness and dynamic mission planning to embedded training and readiness.

- Support a collaborative effort across industry, academia, the Army research community, and the Army analysis community to establish an analytics infrastructure that addresses standards, methods, and tools for training, testing, validation, and verification of doctrine—for example, methods and approaches to interpret and quantify Soldier and joint Soldier-intelligent systems performance for physical tasks and for decision making.

Implementation

- Establish an academic center to develop the science of materials integration to enable the ingestion, circulation, and metabolic transpiration of energy and power for local actuation and computation in a distributed and resilient manner.
- Support internal Army research efforts that focus on materials and subscale functional elements to promote rapid assembly and synthesis of materials across multilength scales, modeling and simulation, and fabrication technology to produce complex multimaterial multifield metamaterials.
- Establish a collaborative effort between the Army research community and academia to develop fabrication and manufacturing processes and procedures to produce multifunctional building blocks unique to intelligent systems.

Discovery

- Support an extramural program in Complexity and Emergence to develop mathematical models for predicting nonequilibrium behavior of complex multiscale systems that advance our understanding beyond statistical physics and nonlinear dynamics.
- Increase the hiring of mathematicians to enhance the capacity for mathematical analysis internal to Army laboratories.
- Support a multifaceted program (internal, external, and collaborative) in Living Materials to develop the principles enabling bioassembly and manufacturing of complex synthetic and biocomposite materials and to identify factors capable of accelerating the process to reduce maturation time.
- Support internal Army research efforts to enhance Army investments in multiscale modeling to accelerate the rate of discovery and understanding in biology by fusing multiscale modeling with bioinformatics.

5. Summary and Concluding Remarks

The 6 meetings reflect those areas ARL considers of critical importance to the Army. The recommendations within each area are intended to show where investment will provide significant new understanding to advance capabilities desired by the Army.

A theme that spanned the collection of meetings was the potential for increased capability if machine learning and AI were manifested across materials and within various length scales and not as an adjunct to an existing system. For example, co-locating computation with actuation in robotic systems benefits both local and global system response. Similar statements can be made about co-locating computation (intelligence) within manufacturing.

A vulnerability discussed implicitly, if not explicitly, in several of the meetings is the need to maintain connectivity across disparate systems, some of which are fixed and others, mobile. Key to this is maintaining a consistent and coherent time base across a distributed and heterogeneous network of networks without resorting to global broadcast methods. This topic requires further investigation.

Appendix. Individual Meeting Summaries

The meeting summaries found in this appendix appear in their original form, without editorial change.

Towards a Science of Complexity

November 9–10, 2016

Adelphi Laboratory Center MD

Organizers: Dr. Bruce West (ARL/ARO) and Dr. Ananthram Swami (ARL/CISD)

Introduction

Organized by the Army Research Laboratory, the Army Science Planning and Strategy Meeting on "Towards a Science of Complexity" took place on November 9-10, 2016 at the U.S. Army Research Laboratory (ARL) Adelphi Laboratory Center (ALC). A new way of thinking is made necessary by the demands of contemporary science to overcome the complexity barriers to modeling complex systems in multiple scientific disciplines across the Army. For example, non-differentiability of turbulent fluid flows, unpredictable transitions of peaceful demonstrations into riots, intermittent instability of decision making induced by physiological and psychological factors (such as emotion), inability to predict the behavior of large heterogeneous socio-technical systems, the catastrophic cascades of failure modes on power grids, computer networks, and so on. Complexity entails the qualitative, as well as, the quantitative richness of phenomena; a delicate balance between regularity and randomness in the nonlinear dynamics.

As a community, we know how to deal with algorithmic complexity, but an algorithm assumes that a problem formulation exists, which in turn means that a mathematical model exists. Today's networks/systems are so complex that we do not have adequate mathematical tools to represent them, or even to talk about the complexity of representation. We need advances in mathematics to deal with this. Things are fairly simple if the world is heterogeneous, but well-mixed, and if we are primarily interested in steady-states. Often we do not have good spatial or temporal mixing, and even more frequently we are interested in transients (because external events occur before a steady state can be achieved). According to physicist Stephen Hawking, the 21st Century will be *the century of complexity* [1]. But that may already be here.

The goal of the meeting was to identify fundamental research issues that need to be addressed, which may enable future military-relevant capabilities. Participants were asked to identify gaps in scientific understanding and describe how to apply existing scientific understanding to establish bounds on performance. The meeting encouraged structured yet open and broad-ranging discussion and exploration of multiple perspectives on the issues.

The following questions provided a focus to initiate discussion:

- What are the emerging mathematical, statistical, and methodological advances entailed by complexity? Assess and validate their suitability to perform complex adaptive analysis of scale-free dynamical systems in extreme hostile stochastic environments.
- What are the fundamental algorithms and models needed to create autonomous systems that can characterize, detect, adapt to adversarial behaviors, and self-heal systems in a heterogeneous networked environment to enable effective situational awareness?
- How do we measure, model, and predict the complex nonlinear dynamics of adjustment, adaptation, and intergroup levels that lead to emergent structure, culture, and physical processes (such as development of adversarial and allied groups, sociocultural conflict, emergent states, critical phase transition, etc.), which involves large-scale collectives, including organizations, crowds, societies, and cross-cultural relations that are critical to strategic planning and Army operations?
- How can automated robust design, discovery, and decision be achieved through advances in optimal information exchange machine-learning/surrogate modeling, combined with physics, big data, uncertainty quantification and optimal verification and validation?

The mathematics that scientists employ does more than simply provide models of phenomena they seek to understand. It provides the language and logical tools necessary to think about those things in a way that enables them to make new and important predictions that can be experimentally tested. The US Army's Operating Concept is to *Win in a Complex World* [2]. The Army must tackle wicked problems wherein objectives and constraints evolve in unpredictable ways. Complexity arises from the increasing heterogeneity, connectivity, scale, dynamics, functionality and interdependence of networked elements, from the increasing velocity and momentum of human interactions and information. Events now unfold in internet time, as noted by the: Defense Science Board (DSB) 2014 Study on Decisive Army Strategic and Expeditionary Maneuver. But complexity science is much more than network science. Increasing integration of knowledge across disciplines requires a systems approach, rather than a reductionist one. The DSB 2013 report on Resilient Military Systems and the Advanced Cyber Threat notes the exponential growth in complexity of operating systems software, and the software required to defend our systems. Increasing complexity in hardware and software points to challenges in testing them.

Consequently, the complexity of the connectedness problems, being addressed by today's society and Army, challenges existing mathematics and often uncovers the tools lacking for an understanding of that complexity. The recognition of the importance of variability as a measure of complexity in the last decade or so, established that to understand complexity science, mathematics must go beyond the analysis of analytic functions, not just in physics, but in the social, ecological and life sciences, as well. Fractional calculus is one way to frame the research hurdles entailed by complexity to answer such questions as: How does a peaceful demonstration become a riot? Other approaches discussed include homotopy type theory (which combines algebraic topology, category theory and logic), network and graph mathematics, as well as, renormalization group theory.

The following notes capture some of the discussion and findings of the meeting.

Mathematics of complexity

Complexity can be given an intuitive interpretation, but we acknowledge that there is no universally accepted definition. A quantitative measure of complexity can be associated with the dynamics of a system and is related to the number of interacting variables. Consider the dynamics of one or a few micro-variables, which is denoted "simple" in the lower left corner of Fig. 1. The mathematics of such systems, as the number of micro-variables increases, includes integrable and non-integrable Hamiltonians, nonlinear dynamics, linear control theory, algorithmic complexity, among other methodologies and are all relatively well understood. However, non-local effects in space and time are not well known even in the case of a few variables. As the number of micro-variables continues to increase, moving from left to right, a system's complexity rises and the known mathematical techniques become less and less useful. The methods blend into what we do not yet know.

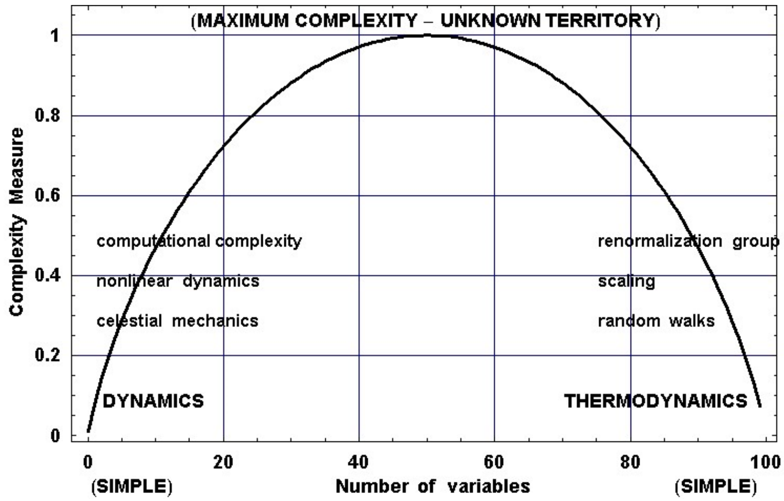

Figure 1: A conceptual nonlinear measure of complexity; one that categorizes networks with one or a few microscopic degrees of freedom and that are described by deterministic trajectories, as being simple. In the same way systems that have a very large number of microscopic degrees of freedom that are not described by individual trajectories, but rather by distribution functions, are also simple. Complexity lies between these two extremes of description [3].

On the far right side of the curve, where the number of micro-variables is very large, we have equilibrium thermodynamics, and the system is again relatively simple. The mathematics describing such systems involve partial differential equations that capture the evolution of probability density functions (PDFs), renormalization group (RG) relations and scaling of the coupling across scales; all of which bolster our understanding of the physical, social and life sciences. Here, the non-local effects in space and time are captured by the fractional calculus. As we ascend the curve, moving from right to left, the phenomena being analyzed increase in complexity, even though the number of micro-variables decreases, the number of macro-variables increases. Consequently, the mathematical tools available again become less useful.

The unknown territory of future science and engineering lies between these two extremes of relative simplicity. The area of maximum complexity, at the apex of the curve, is where we know the least mathematically and have minimal control. It is where neither randomness nor determinism dominates; nonlinearity is everywhere; all interactions are nonlocal in space and time and some things are never completely forgotten. Here is where turbulence lurks, where the mysteries of neurophysiology take root, and the secrets of psycho-sociology of both large and small groups are hidden. All the problems in the physical, social and life sciences that have for centuries confounded the best scientific minds are here waiting for the next mathematical/scientific concept to provide some light of scientific understanding to guide the development of engineering control.

As a working definition, we may consider complex phenomena to have multiple interacting components, with emerging behavior that is entailed by, but cannot be immediately inferred from, the dynamics of its component parts, as would be the case using reductionist descriptions. The nonlinear interactions give rise to a blend of regular and erratic variability in complex phenomena, which enable them to adapt to a changing environment and thereby survive. The dynamics of complex nonlinear phenomena demands that we extend our horizons beyond analytic functions and classical analysis.

The calculus of Newton and Leibniz and the analytic functions that solve the differential equations, resulting from Newton's force laws, have historically been seen as not only necessary, but sufficient as well, to provide a proper and complete description of the physical world. On the other hand, experiments indicate that a broad range of physical, biological and social phenomena cannot be understood using the analytic functions we have come to rely on in physics. These functions do not capture the complex dynamics of common physical phenomena such as earthquakes and hurricanes [4]; everyday social phenomena including group consensus [5], transitions from peaceful demonstrations into riots [6], economic unpredictably as in stock market crashes [7], high frequency finance [8] and healthcare networks [9]; or the familiar psychological activity of cognition and habituation [10]; in computer and communication networks such as Ethernet traffic [11], internet topology [12] and in the understanding of why networks fail [13]. As Perrow [13] notes, catastrophic failures may emerge because of unanticipated interactions in a complex system; mere redundancy may not be effective. The inherent complexity of these phenomena and many others is beyond the scope of familiar nineteenth century analysis, which, to a large extent, forms the mathematical foundation of present day physics and engineering. Understanding complexity as an extended class of problems, with common structural and mathematical properties, requires a new way of modeling and consequently more innovative thinking.

Various books [14] [15] present a variety of strategies for modeling behavior such as entropy, fractal methods, power-law analysis, clustering, and the fractional calculus, to name a few. One approach being addressed is Hidden Markov Modeling (HMM) with non-negative matrix factorization for pattern learning [16], [17]. The general approach is being applied to both permissive environments (full observations) and is being tested for suitability for contested environments (sparse observations). The difference in the situations is the type, amount, and quality of data being assessed. Furthermore, a fundamental question being asked is related to the sampling method needed to learn a pattern.

Phenomena that require the notion of non-integer dimensions, derivatives and integrals for their interpretation were believed by most investigators to be interesting curiosities that lay outside mainstream science. However the increased sensitivity of experimental tools, the enhanced data processing techniques, the vast amounts of data made available by social media, and the ever increasing computational capabilities have all contributed to the expansion of science in such a way that those phenomena once thought to be outliers are now center stage. These curious processes are now described as exotic scaling phenomena, whose descriptions quantify the coupling of variations in phenomena across widely separated scales in both space and time.

We note the lack of traditional dynamic equations in modeling complex phenomena, which have been explored using fractional thinking [15]. Such reasoning is a kind of in-between thinking; between the integer-order moments, such as the mean and variance, there are fractional moments required when empirical integer moments fail to converge; between the integer dimensions there are the fractal dimensions that are important when data have no characteristic scale length; and between the integer-valued operators that are local in space and time, are the non-integer operators necessary to describe dynamics that have long-time memory and spatial heterogeneity. Complex phenomena require this in-between way of thinking and the fractional calculus provides one framework for constructing this kind of mental map [15]. Fractional ARIMA processes have been used to model and analyze Ethernet traffic data, temperature and river level fluctuations [18].

A shift in thinking was accomplished by introducing probabilities to describe large complex system. Empirical exemplars of such complex phenomena are the time intervals between: earthquakes of a given magnitude [19]; solar flares of a given size [20], breathing intervals [21]; events recorded by electroencephalograms (EEGs) [22]; events for optimal storage in human memory [23]. Many, if not all, such empirical PDFs are inverse power law and the average time between events, the first moment, diverges. Thus, the evolution of the PDFs are no longer given by partial differential equations, instead they are controlled by fractional differential equations.

It is important to have some perspective as to the ubiquity of phenomena whose statistics are inverse power law (IPL). They appear to be independent of context, occurring in geophysics, economics, sociology, medicine, astrophysics, computer and communication networks, urban growth, in short, in every scientific discipline from Anatomy to Zoology. The mathematics must therefore capture the complexity described by these IPL phenomena and answer such questions as:

- How can we translate a system's complexity into a language that ultimately is easy to understand when presented to a human for decision making?
- How to quantify the impact of complexity on system manageability, and human understanding and cognition?
- Do we need one leader that understands the entire complex system to some extent?
- Do natural complex systems have a design principle that can be learned?
- Is there a dominant strategy for approaching phenomena that span disciplines?
- How is uncertainty quenched by the flow of information?
- How do we combine machine learning and modeling?
- Are there fundamental limits to the complexity of engineered systems?
- Should complexity be limited? Will simplicity lead to lack of robustness (anti-fragility)? Should (can) complexity be planned (engineered)? And what are appropriate frameworks for controlling complex systems?

Modeling & Learning

Autonomous systems must learn elements of the environment to perform well, which is coupled with supervised training from automation. Likewise, there are dynamic data driven applications systems (DDDAS) approaches [24] to deal with self-healing analysis such as assimilation methods. Key elements being pursued include graphical information fusion methods, advanced methods in nonlinear information fusion such as the Probability Hypothesis Density (PHD) estimation for unknown and varying number of targets, and incorporation of operating conditions to sense and model behavioral target variations. These elements are coupled with the information management approaches such as agent-based systems to compare information for a distributed shared situational awareness through situation assessment or even more challenging is shared situational understanding.

Adversarial behaviors can manifest themselves in many ways; *e.g.*, coordinated misinformation campaigns, campaigns possibly supported by social bots, impersonation, opinion manipulation, censorship by flooding, etc. The effect of adversarial behaviors could be direct (such as subverting a physical link or node in a communications network) or indirect (such as influencing opinion and trust relationships). Supervised and unsupervised approaches are required to detect these adversarial coordinated patterns. Are there fundamental limits to learning adversarial behaviors? What are optimal approaches for rebuilding a network in the face of adversarial actions? Can autonomous agents implement optimal strategies based only on local information?

The modeling of competitive sports has been used to provide insight into adversarial behavior, but one must exercise caution because competitive and adversarial behavior are not identical, although there is overlap. The subtle question relates to quantifying the difference between the two. The categorizing of agents as competitor or advisory often depends on the context and requires models having elements with itemized properties determined by a characterization space for the group of interest. Another difference is that game-theoretic formulations appropriate in this context could involve a very larger number of players, with heterogeneous, partially known, obfuscated and time-varying strategies.

Dynamics of Complexity

There are many nonlinear methods being explored for dynamical analysis. One such example is tracking, from which *cubature* (adaptive multidimensional integration of vector-valued integrands) methods are showing promise. The cubature points are adjusted to determine the uncertainty regions. While loosely aligned with emergent behavior, these types of approaches, when compared with other nonlinear methods, such as Homotopy (continuous deformation of one function into another) methods, are being used as a dynamic data driven application systems (DDDAS) methodology to update the models (models help for next state prediction). The challenge is determining whether or not these physics-based approaches are applicable to aspects of social-cultural-behavioral modeling.

An example highlighting situational awareness is the combination of nonlinear movement predictions from cubature points combined with game-theoretic models of behavior. Thus, the system measures the nonlinear locations, uses a behavioral model, and then predicts the next course of expected action. While applied to single actors, it could be assumed that the behavioral model could also be aggregated to the actions of many actors that combined with intent, could be applied to command and control battle management.

Nearly half a century ago the Physics Nobel Laureate Philip Anderson wrote the remarkable paper "More is Different" [25] in which he speculated on the collapse of reductionism in science, when seeking to understand phenomena of increasing size that encounter difficulties with scale and complexity. The central problem he identified is the shift from the quantitative to the qualitative, which he gathered under the heading of "broken symmetry". In physics symmetry means the existence of different viewpoints from which a system appears unchanged.

Newton appears to have been the first scientist to recognize the significance of symmetry in his assumption that space and time are homogeneous and isotropic, resulting in the law of universal gravitation being scale free. Symmetry is broken as the complexity of a system increases with size, the clearest example of which is the mathematically sharp, singular "phase transition" in which the microscopic symmetry (dynamics) is broken (violated) at criticality. Note that in the modern theory of complex networks, consensus in social networks shares most, if not all, of the properties of physical phase transitions, such as water becoming ice, including the spontaneous change of short-range interactions to long-range collective behavior.

Phase transitions are observed as the consensus reached by social and neural networks, as a parameter that quantifies the interaction strength between the elements of the network is increased to a critical value. This is not unexpected for very large systems [26], but it came as a surprise when networks with as few as 9 members display phase transition behavior in support of the concept of *groupthink*, in which a small group of individuals reach a unanimous decision that is the worst possible and would not had been reached by any individual within the group acting alone [27]. The implications of these formal results are still to be tested in terms of the efficacy of squads carrying out assigned tasks under adverse conditions.

Formally, the micro-scale symmetry is lost to the emergent collective (less symmetric, or equivalently, more complex) behavior at criticality, which arises on the macro-scale and thereafter dominates the system's dynamics. This behavior was successfully explained by another Nobel Prize winning physicist, Kenneth Wilson, with his invention of renormalization group theory (RGT) to describe critical phase transitions in physical systems. Here again the general theory shifts the emphasis from the quantitative to the qualitative to explain the origin of the loss of symmetry. In fact, RGT tells us that the macro-scale symmetry demands that a group as a whole responds to external forces, often in violation of the micro-scale interactions. This is not a settled question in physics, where the whole is not only more than, but very different from, the sum of its parts [25], and consequently one cannot yet predict what is to be learned by applying this new mathematical strategy to the social and life sciences.

The difficulty in measuring complex phenomena can be traced to their lack of a characteristic scale, or said differently, their overabundance of interacting scales. RGT specifies how the various scales influence one another, with no one of them taking over the dynamics. Critical behavior can be anticipated by the existence of 'critical slowing down' (CSD), which is the decay of a perturbation becoming increasingly slower as a phase transition is approached. CSD might be the precursor to failure, which in itself is a qualitative change in the group dynamic.

The notion of failure presupposes the existence of a model of a system's functionality; a model that is either formal or informal. The most desirable model is quantified mathematically, since this is the simplest to unambiguously communicate scientifically and would be the most straightforward to verify experimentally. Of course, such a model is typically not available and most often the dominant variables with which to describe the system's dynamics are unknown. Consequently, even when a potential model exists, it must be deduced from the data, for example, using Takens' embedding theorem for attractor reconstruction [28]. But then, of course, one encounters the difficulties of data limitations and consistency. Another approach would be a universal machine learning model, which does not exist, and if it did exist would require criteria for determining when it had enough data.

Interfacing Complex Models

The discussion on robust design and optimal information exchanges focused on the interfaces between models at different scales / fidelity and the inherent problems fusing a system's model from models of individual components. There are multiple challenges in describing, modeling and controlling heterogeneous systems that combine physical, information, and human elements, operating at different time scales, and represented by different mathematical and non-mathematical models. Users want tools and methods to reduce complexity, however only a few sets of studies have investigated physics-based and human-derived data aggregation for situation awareness [29].

The following gaps were identified:

- Design-centric modeling (Translate uncertainty to human-understandable terms; e.g. when to evacuate from hurricane)
- Information exchange: How do we communicate between different computer models/codes? Can we automate code refactoring (to automate generation of computer models of a complex system from models of its components)
- Surrogate modeling that identifies low-dimensional manifold from high-dimensional manifold of parameters
- Multiscale modeling: Space, time and physical domains (interrelated)—each has its challenges: methodologies needed

- Machine learning from small data sets, and under adversarial conditions
- Propagation and aggregation of uncertainty in complex systems; ability to deal with rare events

Note: Much (most) of this is needed now, not 25 years out.

Summary: A number of conclusions drawn within the workshop overlap with those reached by the ERA Gap analysis.

Predicting non-equilibrium behavior

- A formal mathematical definition of complexity and its quantification is lacking
- There is critical demand for mathematical models of finite size, far-from-equilibrium, complex multi-scale systems, beyond statistical physics and nonlinear dynamics

Lack of physical principles

- We do not understand how the emergent dynamics and intelligence of heterogeneous collectives respond to externally imposed gradients or current densities.
- Need to quantify sources and control of uncertainty and failures in complex systems

Control of Information Exchange

- Require theory for how information exchange controls automated robust design, discovery, and decisions that includes big data, uncertainty quantification, failure, and optimal verification and validation

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Neural Inspired Artificial Intelligence

November 29–30, 2016

Aberdeen Proving Ground MD

Organizers: Dr. Brian M. Sadler (ARL/VTD), Dr. Piotr Franaszczuk (ARL/HRED), and Dr. Raju Namburu (ARL/CISD)

AI and Machine Learning Vision: The Army seeks to develop and employ a suite of artificial intelligence (AI) and machine learning techniques into systems to assist soldiers in complex operational conditions. These AI systems should be robust, scalable, and capable of learning and acting with varying levels of autonomy, to become integral components of networked sensors, knowledge bases, autonomous agents, and human teams. Potential far-reaching applications include discerning adversaries' intent, supporting course of action analysis, providing real-time perception for rapid op-tempo autonomy, and developing intelligent adaptive soldier training.

Objective & Scope: Many advances in AI have been informed and inspired by cognitive and computational neuroscience, which is leading to new computational algorithms and circuit architectures. The workshop objective is to determine new and long term research issues and areas to enable neural-inspired AI processing architectures that support the Army AI and Machine Learning Vision.

The meeting brought together a unique mix of research leaders in neuroscience, brain imaging and computational modeling, vision, artificial neural networks, artificial intelligence, cognitive computing and circuits.

Focus Areas:

1. *Computational brain modeling.* Multi-disciplinary advances have led to enhanced understanding of neural processes. This session considers the trends and future of brain modeling with links to potential Army use.

2. *Brain-inspired architectures and processing.* Inspired by advances in brain modeling, a variety of processing architectures have emerged, including single neuron models, deep neural networks, recursive neural networks, and others. These architectures have various tradeoffs and are typically tuned for a specific application. This session considers the future of architectures, such as modular composition and layered representations, and their implementation in HPC's and dedicated devices.

3. *Data representations, training, learning, and applications.* Data representation has emerged as a critical aspect of abstraction before processing, especially with

mixed modality inputs that can enable a general processing architecture to be effective for multiple applications. This session considers research issues associated with data abstraction, training and learning, as well as emerging and potential application areas for the Army.

Background:

Optimism with respect to AI and autonomous systems is due to recent advances in some key component areas. Technology convergence continues to unite networking, processing, sensing, and control onto portable devices and robotics. This follows general mass production trends in cellular networking, robotic, and sensor technologies.

Artificial neural networks (ANN's) have exploded into a variety of applications since 2010. While the basic ANN technology dates to the 1990's, two trends have enabled their recent emergence. First, digital processing technology has advanced (i.e., Moore's Law). ANN processing has been mapped onto graphical processing units (GPU's) resulting in orders of magnitude speed-up. Second, training data sets are now available at the scale needed to ensure good statistical performance with brute-force gradient descent learning algorithms. These data may be on the order of millions of instances, each with ground truth to enable supervised learning, and are expensive to collect and organize. As big-data training became feasible, a large number of experiments have shown the empirical usefulness of ANN's.

Embraced by the largest US commercial enterprises such as Google and Facebook, ANN's have been very successfully applied in areas such as image processing and vision, natural language processing, robotics, multi-agent systems, and others. They have displaced decades old technologies in image and speech processing. ANN's are now better than humans on some kinds of visual object and word recognition, not to mention gaming. Recursive neural networks (RNN's), also dating to the 1990's, enable sequence processing, such as sentences or video frames. Combined architectures can be used for fusion of modalities, e.g., imagery and audio are combined for the visual Q&A problem, where natural language processing is combined with vision, so that questions about the image may be posed to the system.

Parallel advances in the mining of big-data to produce knowledge bases (KBs) has produced systematic methods for the storage, assimilation, and association of data, enabling rapid querying and information retrieval. Knowledge bases form the memory of intelligent systems such as IBM Watson, in game playing architectures, and numerous other applications. Machine learning (ML) can be thought of in this vein, exploiting data to learn and specify models that can make predictions. ML is often viewed as a subset of AI.

While these advances are significant and even dramatic, the long term question of intelligent systems and general AI for Army applications is reliant on fundamental long-term multidisciplinary research in areas such as neuroscience, signal processing, and computer science.

The ANN, KB, and ML technologies mentioned above are geared to specific applications, whereas general AI seeks a much grander goal. Consequently, general AI is the subject of a great deal of fascination, speculation, and science fiction.

Gaps and Recommendations:

The interplay between neuroscience and computational architectures, AI, and machine learning has been fundamental to the advancement of AI. We lack a fundamental science of intelligent architectures that incorporate control (action), knowledge bases (memory), and human interaction. Consequently, AI architectures are typically built upon neural plausibility, and empirically driven for some specific application. Learning from biology has been key to AI, leading to the development of the theoretical model of ANN's, and the combination of biology and artificial systems was common initially. However, over time the research split into two distinct approaches, one focused on improving neural models, and the other focused on application of early brain models to AI. Today there remains a large gap between neuroscience and computational neuroscience (brain modeling), and current AI architectures and their application. The multi-disciplinary combination of neuroscience and AI based in computer science and engineering remains relatively rare. This combination should be enhanced, benefiting both AI and brain neurology through interaction and cross-fertilization.

A fundamental science of AI systems is needed that are:

- Heterogeneous
- Distributed / networked
- Modular with composability, and map to efficient hardware
- Readily embedded into applications
- Not reliant on massive supervised training data sets, enable incorporation of prior knowledge
- Have distributed memory
- Can be updated, are adaptable and plastic, unlike current fixed ANNs

- Couple cognition, control, learning, and human teaming
- Robust and resilient in combination with Army networking

These broad goals contain several critical Army elements that are unlikely to be addressed by commercial enterprise. Tactical application is reliant on heterogeneous architectures across Army platforms, networks, sensors, and processors. Distributed operation is essential and must be resilient to attack, mobility, and network failure.

Cognitive architectures should acquire the above features and be directed at specific Army applications. Many architectures have been proposed in the past few decades, but have only weak links with distributed application and other key Army aspects. These architectures should be engineered to enable modularity and composability, to incorporate autonomous agents, and human interaction. They should be linked with control and learning to enable active attention and problem solution in time critical tactical scenarios.

Data abstractions and representations are key to the success of AI. A great deal of evidence shows that AI architectures may succeed or fail depending on whether an appropriate representation and dimensionality reduction approach is applied. However, there is insufficient understanding and theoretical underpinning for this problem. A continued research emphasis on dimensionality reduction methods, new measures of information, and their interplay should help.

Links are needed between ANN architectures and theoretical AI designs. While ANNs have advanced empirically, the theoretical underpinnings are lagging. Early work in layered representations should be accelerated, to provide systematic design principles and direct match with applications, incorporating tools such as graph signal processing and nonlinear signal decompositions.

Incorporating prior knowledge is key to reduced training cycles and use of unsupervised learning. The limitations of big-data supervised training are now apparent, and pose significant barriers to rapid application of AI in Army scenarios. It is critical that analytical frameworks be found that enable the incorporation of prior knowledge, such as the combination of Bayesian methods and other AI techniques, along with the study of development and learning in biological neural networks.

AI and action should be coupled. Active perception, focus of attention, motor control, and other cognitive programs are evident in neurology. These techniques should be explored and developed for the combination of AI and robotic autonomy in dynamic Army settings, e.g., in task based models. There are large fundamental gaps in understanding of the use of memory and attention in AI. Recent neuroscience has demonstrated focus of attention mechanisms, e.g., in vision, varying in time over spatial and resolution scales. Long term multi-disciplinary study is needed to develop the science and practice of action-oriented AI.

Beyond human sensing: AI should be applied for Army sensor fusion and processing. The recent success of ANNs has demonstrated early progress in fusion of audio and vision. These techniques should be expanded upon and applied to Army problems, e.g., the fusion of EW, IR, and active sensing. Long term research issues include fusion over different sensing and time scales, and coupling with action-oriented AI to enable autonomous mobile sensing platforms.

Distributed AI is needed for tactical application. Distributed intelligence is not a current research emphasis in the AI research community, although some limited aspects might emerge commercially due to dense internetworking and off-platform computing. Distributed intelligence is critical to Army applications, and should be coupled with cognitive networking to provide resilient AI systems. Advances in neuroscience are leading to understanding of neural structure, function, and networking within the brain, providing new insights into the functional components of intelligence and how they interact. Emerging understanding in network science, graph signal processing, and other new mathematical tools may bring mathematical modeling to an often empirically based field.

Active learning is needed over different time scales with adaptive cost functions. Neuroscience now provides preliminary understanding for how learning is continuous and adapts and changes focus over time. A fundamental science of learning is needed that leads to algorithms capable of these more general learning attributes, and that couples with control to enable active learning.

AI and memory should be co-investigated. Human memory appears to be massively distributed, providing resilience and robustness. Long term memory consolidation in humans appears to be a slow process, whose understanding is likely to provide new insights into AI architectures and processing. Neuroscience studies and knowledge bases and other computer science memory constructs should be co-investigated to advance fundamental understanding and provide new memory architectures and algorithms, with tight coupling to active learning and distributed AI.

A fundamental new science of human-AI interaction is needed. Human-machine teaming is largely heuristic, and theoretical underpinnings are needed to develop systematic design methods. Psychological insight, mathematical modeling, and systems engineering must be combined and not left to separate research avenues.

The science of interaction should encompass multi-modality, including speech, vision, gestures, virtual reality, and brain-computer interfaces with wearable sensors such as EEG. AI designs must incorporate the ability to query humans in two-way dialog, for learning, understanding, and task oriented teaming.

Circuit architectures are critical. SWAP constraints and reliance on wireless networks will continue to frame the achievable AI for Army scenarios. While commercial success of AI will drive circuit development for mobile applications, it is incumbent on the Army to discover canonical architectures that provide modularity, to enable dedicated circuit designs that have broad Army applicability. While this paradigm has been successful in Army applications such as cognitive radio, we currently lack a science of AI modularity and architecture composability. Tools are also needed to move AI algorithms to embedded applications. Long term, it is important to consider going beyond the classic Von Neumann computing paradigm for some AI components.

Data collection and large scale experiments should focus on Army relevant scenarios. Data collection will continue to be important to support appropriate experiments in the long term. As AI systems emerge, they will become increasingly complex and multi-platform, creating challenges for large scale experiments, including the need for costly research infrastructure.

Conclusion:

The development and combination of AI technologies has the potential for significant payoff in future Army systems. Advances in neuroscience are leading to understanding of neural structure, function, and networking, providing new insights into the functional components of intelligence and how they interact. Focusing AI research on the key Army issues will leverage commercial advances and accelerate system development, with the strong potential for leap ahead capability.

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Invited speakers:

- Kwabena Boahen, Stanford University
- Richard Granger, Dartmouth University
- Barry Horwitz, National Institute of Health
- Adam Marblestone, Massachusetts Institute of Technology

- Ernst Niebur, Johns Hopkins University
- Aude Oliva, Massachusetts Institute of Technology
- Kate Saenko, Boston University
- Thanos Siapas, California Institute of Technology
- John Tsotsos, York University (Canada)

Bioenabled Materials Synthesis and Assembly

December 1–2, 2016

Aberdeen Proving Ground MD

Organizers: Dr. James Snyder (ARL/WMRD), Dr. Shashi Karna (ARL/WMRD)

Co-Organizers: Dr. James Sumner (ARL/SEDD), Dr. Josh Orlicki (ARL/WMRD)

Introduction:

Biotechnology is a fast growing sector of the economy. Recent advances in systems and synthetic biology, the associated high throughput screening methods, and genetic editing tools have allowed for holistic engineering of biology. This may enable point of need and lower cost generation of chemical feedstocks and materials. Further, biological systems inherently produce spatially designated assemblies of complex hierarchical structures with extreme precision. Biotechnology may uniquely provide the DoD novel high-performance materials not accessible through traditional synthetic and manufacturing approaches and offers the potential to impart disruptive living material characteristics such as re-healing, adaptability, and dynamic, programmable properties.

The Bioenabled Materials Synthesis and Assembly ASPSM gathered thirty participants, including top university professors from across the country, to explore the fundamental questions and anticipated tools to command and control biology to achieve new materials and disruptive capabilities for the Army that are *not available through traditional synthetic and processing methods*, such as non-thermodynamically accessible material states; multimaterial hierarchical assemblies with precise chemistry and architecture at the atomistic and molecular scales; and materials that dynamically respond to stimuli with desired response through changing conditions. Opportunities were discussed for *coupling dynamic synthesis with precision assembly* to define bold new approaches to material development that exploits unique benefits of biology. In particular, the unique structure/function relationships, error/fault tolerances, robust and diverse stimuli responses, and dynamic interfaces that abound in biological systems are of great interest. Consideration was made for *relevance to all material categories* as well as heterogeneous systems, with particular interest in robustness of biological machinery and living products under *non-aqueous and extreme conditions*.

The workshop structure was modeled on that of last year's Microscale Adaptability ASPSM, which utilized a non-traditional dynamic format emphasizing participant input to develop the focus areas of the workshop. Academic participants presented concise 3 minute summaries of their research as it relates to the topic, which provided the group a comprehensive and diverse perspective of the current state-of-the-art in synthetic biology, biotemplating and related materials science. Participants were then organized into small groups to identify long-term scientific opportunities for coupling dynamic synthesis with precision assembly across all material categories and to define bold new approaches to material development that exploit unique benefits of biology. Subsequent breakout sessions addressed research pathways and critical scientific breakthroughs required to achieve those opportunities, particularly in conditions austere or extreme for biological function, and anticipated technological capabilities enabled by this research. The composition of the small groups was reshuffled for each breakout session to allow for different pairings of ideas and styles as the workshop progressed. The rest of this report details output from the workshop as a whole within the categories of opportunities, pathways, challenges and resulting capabilities.

Recommendations and Opportunities:

Long-term opportunities

State-of-the-Art (SOA) Technologies in synthetic polymer synthesis and assembly via chemistry can generate polymers with large diversity, *but cannot be implemented in a template-directed manner*. Living polymerizations can yield some block-level and statistical control over monomer sequence that can extend to some control over polymer architecture through branching units and sidechains but *lack information control in the monomer sequence*. Solid state synthetic approaches yield oligomeric materials with defined sequence, but *lack the error correction mechanisms* and are limited in terms of accessible scale and compatible chemistries. At the next scale, nanostructured functional materials based on polymers can yield hierarchical assembly to some extent but are *limited in control over system dynamics and very limited in control over system integration*.

Biological organisms have several potentially useful characteristics to consider as a basis for designing new approaches to material synthesis and assembly that address the deficiencies noted above. Organisms can reproducibly *assemble precise, scalable, template-directed products* of protein polymers, although they are generally constrained to the 20 canonical amino acids with limited expansion to post-translational substitution or unnatural monomers at this time. Organisms can *sense or detect even minimal changes to their environment* regarding light, temperature, pH, pressure, metabolite concentration, etc. Organisms can then generate a chemical, physical or electrical *response to maintain operational equilibrium* or performance, known as physiological adaptation. Communities of organisms may also collectively respond over time by evolving to *maintain* *optimized performance under changing conditions*, known as genetic adaptation. Through these forms of adaptation, organisms can operate with *energy efficiency* and through use of environmental energy sources and local feedstocks. Organisms can also generate, store and transmit *complex multivariate information*. Multiple organisms can then demonstrate complex functions through *collective and coordinated active behavior*. Finally, all of these functions may be augmented through direct human intervention as organisms are mutable and can be modified for target properties e.g. through selective "breeding", through forced evolution and through direct modification (e.g. DNA sequencing).

Opportunities and challenges in using biology towards synthesis and assembly of materials may be very different depending on how biology is being used. Approaches may range from bioinspired, in which design lessons learned from nature are replicated using conventional chemical or mechanical synthetic approaches; to bioderived, in which material is harvested from biological organisms then used in a synthetic material; to biosynthesized, in which biological organisms are used as the direct mechanism of synthesis and assembly of the target material. While the intention of the workshop was to focus predominantly on biosynthesis, relevant opportunities within the other methods were also considered. In addition, consideration was made for the recent emergence of "living materials", a hybridization of living organisms and nonliving materials that has significant overlap with biosynthesis and can include many target materials that are still living even in functional applications.

The groups identified several potential advantages of using biological organisms for synthesis vs. traditional methods:

- Diversity: Harnessing and expanding the rich palette of biomolecules (e.g. DNA, RNA, proteins, orthogonal polymers, etc.) and biomanufactured materials to go beyond petrochemical building blocks and traditional chemistry. Chemical security and improved domestic manufacturing capability are additional benefits.
- On-demand: Biomanufacturing may be turned on or off, and rate controlled, through control over metabolite concentration or environmental conditions
- Efficiency: Biological entities can be very energy and feedstock efficient during synthetic processes. As the technologies discussed here mature, there is promise for low cost of production.
- Spatial control: Biomanufacturing may yield dynamic control over three-dimensional material architecture

- Temporal control: Synthesized output can be changed through changes in metabolite or environmental conditions
- Fast adaptation: Bacteria, viruses and other rapidly evolving organisms may be used to adapt synthetic output to changing conditions
- Information-based robust materials: Evolve "better" and chemically diverse biomolecules (e.g. DNA, polypeptides) for
    - Orchestrated control over structure and motion that adapts and evolves in 3D, which may require additional foundational development of the requisite chemically dynamical linkages to enable these adaptive characteristics.
    - Coordinated behavior (e.g. sensing, processing and response characteristics) of collective materials.
    - Information-encoded polymers based on complex hierarchical functional structures.
- Bio-based materials provide opportunity for self-limiting and self-replicating control over information flow and energy flow in a closed system.

Considering these factors, the academic participants provided significant input regarding the long-term research opportunities and challenges within the scope of bio-enabled manufacturing. This input brought forth and clarified the following three critical topics:

1. How do we design, store and implement instructions for materials synthesis and assembly? Cells are a coexisting blend of precision (deep energy wells) & disorder (dynamic response/variability).
    a. How do we provide the consolidated instructions for complete synthesis and assembly? Working with current biological building blocks this could include for example DNA, peptide based assembly, or carbohydrates.
    b. How do we enable biosynthesized materials to inherit properties and advantages of the parent biology such as sensing, adaptation, switchable operation, and self-healing? Properties such as these may be critical for interfacing materials to living systems such as the human body.
    c. How do we enable spatial and temporal control over assembly of the material architecture? This capability might include tracking the process

via feedback in real time and using active control to steer it to a desired outcome. The phrase "dynamic orchestration" was considered.

d. How do we provide instructions to encode out-of-equilibrium higher organization and function? Particular value may be placed on dynamic systems with active energy transduction.

2. How do we make living synthesis / on-demand biomanufacturing robust to extreme conditions including pH, temperature, non-aqueous environments?

3. How do we construct materials with autonomous sensing, learning and evolving of integrated functions and/or architecture?

Pathways towards meeting the identified opportunities

1. *How do you design, store and implement instructions for materials synthesis and assembly? How do we consolidate those instructions and enable inheritance of properties, spatial and temporal control over assembly, and out-of-equilibrium higher organization and function?*

Cells have the ability to design and implement instructions for synthesis. There is a lot of emphasis currently on top-level regulation. Intermediate changes to a cell may be possible by changing RNA and related molecules. Viruses use this approach to assault cells by knocking out the internal genome and re-writing them to achieve a minimal & efficient function. There is less emphasis on the proximal pathways that actually create materials via active sub-units/sequences. This latter approach is worth considering. Large parts of the genetic code may be involved in logic mechanisms and provide a basis for implementing instructions for synthesis and assembly. A worthwhile but challenging goal is breaking down hierarchical levels of cell function to manageable sub-units. Analogous to circuits, it may be possible for cells and their sub-functions to be used as "subroutines" for existing systems. Programmable control over active sub-units may then be used to create designer materials. The enabling capability would be the implementation of multiple synergistic metabolic pathways in a single cell, or the coordination of multiple cell types in a system from a designed starting point.

The information required to develop biological subroutines, and to further encode and sequence those subroutines to make a material, is unknown for many organisms and must be discovered. A suggested initial approach is to study organismal systems that possess the properties of interest to understand organismal growth of structures and underlying design rules. Examples include organismal production of magnetic nanoparticles, for which the mechanism is well defined; production of photonic crystals to exhibit a wide range of colors e.g. in butterfly wings and peacock feathers; production of pigments such as melanin and carotene; and production of structural materials such as chitin and cellulose. The target of this discovery and design process would be a library of primitive functions that may be used to develop programmable biological subroutines pertinent to material synthesis.

Applicable use of programmable biological subroutines further requires understanding of how to string the primitive functions together to achieve a desired chemical architecture. There is a need here to harness self-organizing strategies for complex/multi-component systems. This is a complex problem that must accommodate self-assembly of physical architecture and specified function across multiple scales, preferably with built-in feedback mechanisms to guide the process and undertake repair as necessary. The library of subroutines may be considered as “genes” for bio-enabled materials synthesis. To execute this type of research there is a critical need for tools to design genome complexity. We are currently able to program molecular level order of DNA scaffolding. It is less clear how we harness intrinsically non-designable systems. This need highlights a theory gap. Current capability allows us to go from a genetic starting point to predict the grown system, but we lack the understanding to extrapolate back from a targeted end-point back to the genetic origin. Cellular automata-type approaches that define interactions and watch a system grow are not appropriate here, it is the inverse problem that needs to be solved. The first step will be defining the fundamental capability that allows us to solve the problem using computational methods. It is helpful to consider analogous systems. In origami the fundamental capability is a fold, and it is now possible via computational origami to draw any final outcome and then derive the fold instructions. Application of this concept to biomaterials led to DNA origami, which further experienced exponential growth in the design space when non-symmetric folding was enabled. Biomimetic approaches to new materials might consider further exploring this concept with PNA or LNA in the near-term. In biomanufactured systems, challenges arise from vast energy landscapes with multiple energy wells. Chaperones or analogous approaches may be necessary to promote folding or other fundamental capabilities.

Spatial and temporal control over assembly is an intriguing problem that may demand synthetic methods and/or target materials that are stimuli responsive, re-configurable and switchable. Biosynthetic systems can be responsive to multiple stimuli that steer microbes into desired functions or architectures. One route may be to use 3D printing to grossly arrange cells. Further combining light activation with 3D printing may yield orthogonal/complimentary spatial/temporal control. Engineering materials that are dynamic as part of their properties (dynamic equilibrium) might further enable reorganization after a material is formed. For self-regulating synthetic systems there is a need to be able to tune equilibrium end-state for a continuum of products.

2. *How do you make living synthesis / on-demand biomanufacturing robust to extreme conditions including pH, temperature, non-aqueous environments?*

Living systems and their subcomponents are typically not robust to “extreme” environmental conditions such as temperature, pressure and pH. Extending the operational range is a big challenge. For nonliving targets and availability of a more controlled synthetic environment, bioproduction followed by removal or conversion of the living scaffold can sidestep operational constraints. Once the target material is constructed it will have same properties and environmental robustness, as any solid-state material. However, these approaches do not address the fundamental intent here to develop more robust living processes. One approach may be to develop support systems that address specific challenges, for example bio/abiotic vasculature that deliver nutrients, or exoskeletons that shield the sensitive components from heat, pressure, or other stresses.

Engineered biosystems may be a better overall approach, such as enabling synthesis through control of the metabolic machinery of a cell, which may be on-demand based on environmental conditions or triggers. Traditional requirements to culture organisms to engineer them may no longer be necessary given recent developments for delivering DNA into cells *in situ*. In addition, some robust platforms already exist as a starting point. For example, black fungi found in Antarctica and subjected to experiments on the International Space Station are renowned for their ability to live under the harshest of conditions. Eukaryotes, including fungi, are amenable to genomic engineering, but only a few modules are available. The pathways of eukaryotes are not well explored, especially thermophilic eukaryotes.

Similar to the previous section, it is suggested that the problem of “hardening” biological functions and mechanisms be addressed through development and design of fundamental building blocks that are designed to interface with each other. Many pathways work with the inherent adaptability behaviors of biology that already enable survival under hostile conditions, for example to develop antibiotic resistance. Four suggested categories with pathways to improved behaviors are:

- Microbes (e.g. bacteria): Advantages include highly efficient metabolic processes that enable low energy operation and limited waste, and evolutionary adaptability to new conditions or to develop new capabilities including operation under extreme environments. Pathways to better engineering:

  - Improving culturability through a focus on microbes in the mixtures, growth media and nutrient needs, including isolated systems and co-culture
  - Developing genetic tools to interrogate or modify isolated systems and that apply to non-model systems
  - Identifying appropriate bacteria to develop target capabilities or survival skills
  - Manipulating inter-cellular communication by interfacing with other engineered nanomaterials that provide cues
- Biomachineries (e.g. ribosomes, mitochondria): Advantages include scalable, fast, energy efficient synthetic processes with high fidelity and error correction, and ability to be abiotic, multi-enzyme and cell-free. Pathways to better engineering include:
  - Enabling operation in non-biological environments
  - Understanding assembly and motion including system dynamics, multi-component assembly
  - Reconstituting the native function in non-native state
  - Isolating biological parts to reconstitute and re-assemble them into functional elements
  - Engineering biotic-abiotic interfaces
- Biomacromolecules (e.g. proteins): Advantages include native hierarchical structures, chemical diversity available, monodispersity, dynamic operation, ability to synthesize nanomaterials and other structures with high precision and selectivity, ability to combine various building blocks toward multi-functional materials. Pathways to better engineering include:
  - Understanding structure-functional relationships in extremophiles
  - Developing enzymatic pathways under non-biological conditions
  - Understanding protein folding and enzyme evolution to function
  - Developing the biotic/abiotic co-assembly
- Biotic/abiotic hybrids: A complex approach with challenges involving multi-component interactions at various lengthscale that may be addressed through multi-scale modeling and informatics

3. *How do you construct materials with autonomous sensing, learning and evolving of integrated functions and/or architecture?*

Biology has an advantage in that it is more than just an assembly of materials. Biology can respond to a huge range of stimuli including physical/mechanical, chemical, optical and electrical. However, *controlled* use of living materials requires new paradigms for instructing individual cells and their subcomponents, including the methods suggested in the sections above, as well as for organizing cells across wider morphologies. Coordination of multi-cellular systems in particular will require greater understanding and control over signaling and communication. Three classes of materials were considered:

i. The first class includes non-living products, which may be defined here as materials generated by biology but there is nothing alive in them after production or in use. Preferably, these are materials that are biologically produced but don't exist in nature and cannot be synthesized through other methods. Complex and high performance materials will not be readily achieved using combinatorial or biopanning techniques. Directed evolution is a compelling approach that provides significant potential to address complex problems for which current chemistry and materials science approaches are inadequate, such as high performance adhesives. It may also be used to develop research capabilities, such as designing screens or selection for cells with certain material properties, or evolving cells as nucleation centers or organizational scaffolds. However, successful application of directed evolution approaches to optimizing materials properties will require new selection pressures to produce integrated functional and architectural properties. How to select for materials properties was in fact determined to be one of the key challenges for this approach. The evolution process must be sped up and selection criteria made more complex to better select for performance. Biology has already solved the problem of transport against concentration, so one place to start developing directed evolution techniques may be to explore improving membrane characteristics, such as balancing selectivity vs. flux. Consider amyloid films with a distribution of multiple channel types, each responsible for distinct ion transport. The challenges here would include achieving the necessary channel assembly and distribution to control membrane permeability.

One suggested directed evolution approach, referred to by the group as "Bionic Spores", is to introduce unique and possibly non-biological target material to cells (e.g. a specific crystalline polymer or inorganic nanoparticles) and let them evolve to use it for an improved property such as temperature hardiness. The introduced material may then be slowly removed from availability over several generations and exchanged for desired feedstock (e.g. the relevant monomer or precursor), with selection pressures intended to favor rudimentary synthetic machinery for the target material. This process may be iterated to build up complex machinery that digests certain feedstock, breaks it down to the necessary components, and rebuilds the target with precision, efficiency and self-sufficiency.

Another suggested directed evolution approach, referred to by the group as "Artificial Darwinian Systems", requires an initial diverse library of biosynthesis capabilities; application of a typically non-required function to stimulate forced adaptation; and methods for the selection and propagation of successful candidates. The library must link stimulus and response to survival, such as food source conversion, but must also be linked to a function that may be traditionally thought of as non-biological. Stimulating adaptation may require utilizing additional materials to structure the environment to direct evolution towards the target solution. For example, if the target is a coating that protects against a given stress such as radiation, one method may be to feed a surface of bacteria that are then killed and sloughed off via that stress. Selection characteristics must be based on a full matrix of biological stimuli and response such as physical, mechanical, chemical, optical, electrical, or any combination thereof. The method should also have an integrated computational approach to accelerate learning and success.

ii. The second class includes living systems that generate materials with living biology included. These systems may be continually evolving in the field. Target materials will need to accommodate demands of living cells such as timescales, mass transport, signal transduction, DNA recording and implementation for events, and life support requirements such as diffusion of nutrients and energy donors and acceptors. Mechanisms regarding materials inheriting properties from the "parent" will need to be better understood, as well as how the living components can be controlled to be responsive or non-interactive on demand. Long-term stability of the living function must also be addressed, such that decedents maintain the desired function in the face of exposure to wild-type organisms and operational environments.

iii. The third class includes living materials with dynamically responsive or latent activity, such as materials generated that may have living biology added at a later time when its function is needed. An example might be a healing (or repair) ointment which has organisms in it that are activated at time of use. Catalysis is another relevant application that can draw from enzymology. A concept labelled the "Infinite Tea Bag" considered cells packaged or engineered to survive extreme conditions/storage that can be revived to manufacture proteins or other biotechnology product. The packaging of the cells, such as with a membrane, could act as integrated purification of feedstock or product depending on the flow conditions during use.

Challenges

The workshop included a very diverse group that represented expertise across biology as well as chemistry, physics and materials science. Over the course of two days of discussion this group identified that a significant challenge to many of the biomaterials opportunities is the lack of connection between the research spheres of "biology", which provides much in the way of new design approaches and new tools, and "materials science", which provides not only traditional design approaches and tools but also a mature understanding of how to anticipate and work to meet application needs. Without direct communication between these groups it will be difficult for materials scientists to articulate what a high level application would need at the biological level, and biologists don't necessarily know enough about the materials science to know what materials and materials properties are useful or novel. One suggestion was for more people to be trained in both disciplines to act as intermediaries. In addition, it was suggested that the materials science side, and end users, must be educated to be patient so as to allow biological sciences to mature to where they may be used to address materials needs, since early bio efforts are not likely to solve the problems quickly. "Living materials" solutions that have promise to provide complex and highly functional materials solutions are anticipated to be even more far future. In the near-term, it was recommended that a workshop be implemented to bring together materials scientists and biologists with tutorial components to provide a common language.

Several underlying technical needs were identified as common challenges across the biomanufacturing opportunity space. The most prominent are the need for fusing multi-scale modeling with bioinformatics and the need for new characterization tools that address biological scales, environments and material types. Regarding the former, improved meso-scale modeling and other computational tools are critical to enhancing our understanding of biosynthetic processes as well as narrowing the design space. Bio-informatics need to be incorporated to expand design and evaluation capabilities, but given the level of complexity in these systems there are current challenges with data analysis that will need to be resolved.

Regarding characterization, there is a lack of imaging capabilities for complex heterogeneous materials, systems and interfaces. The ability to determine structure and characteristics is limited and resolution is poor for biological, soft and non-crystalline materials. For example, the suggested direct evolution development of semipermeable amyloid films in section 3 above would require angstrom level resolution in order to test functional capability of individual ion channels. Interfaces, with relevant interactions at the nanometer scale, are another challenge. This is in part because high vacuum and cryogenic techniques are largely not compatible with wet systems. Dynamic behavior of biological systems is particularly difficult to observe, though neutron scattering is a consideration. There is a similar lack of chemical analytical tools to characterize hierarchical structures constructed by biology. It is unclear what level of precision is even needed and what relevant information can be learned using current techniques. Tools or protocols will also need to be developed to screen for materials functionality.

There is a desire to overcome the current challenges and limits regarding the scaling of bioproduction to very large macroscopic structures. There are currently many applications on the nanometer to millimeter scale driving research. There is also an argument that merely scaling up is not a scientific question and the "market" (industry) will take care of it for certain classes of materials that people find most interesting. It was determined that this is not entirely correct and there are also critical scientific questions within this context. It was also suggested that industry taking the lead will depend on the economics, and it is unknown whether the current economics of chemical synthesis will hold up or break down as we scale up. The value-added proposition for bio-enabled synthesis will be governed in part by the complexity of products obtainable and the relative challenge of producing a near-peer compound through traditional synthetic means.

There is high potential value to understanding and utilizing various types of materials that lie between living and nonliving, for example cells without genomes or in vitro systems improved with maintenance factors. There is particular need for materials that interface functionally and dynamically between biotic and abiotic materials, including controlled assembly and disassembly. To facilitate this and other advancements, there is a biotic/abiotic language gap that must be addressed.

Capabilities and Applications

This final section addresses end-use capabilities that the opportunities stated here could provide. The capabilities may be subdivided rather evenly as those that support more advanced research and those that support more advanced end use application.

Regarding capabilities supportive to research, many of the ideas generated have already been discussed as part of the sections above as they are largely challenges within the sphere of biology. Examples might be a toolkit of biological catalysts (such as chaperones, nucleases, and polymerases) to control assembly of non-biological materials, and the ability to integrate patterning of cells and (bio)polymers precisely and aperiodically. Another example was described in the "Bionic Spores", which utilized the notion of introducing unique material or functions to cells, a desirable capability that would further many other applications as well. Feeding nanoparticles to cells for them to uptake and incorporate into structure or products could yield biologicals that make traditional non-biological materials as well as dynamic materials that function using nanoparticles.

Regarding capabilities relevant to end use application, where controllable bioenabled synthesis and assembly provides actual value and successful implementation will depend in part on logistical efficiency, environmental robustness, and what unique products it can generate not available through traditional synthesis and manufacturing efforts. A few ideas are listed below:

- Understanding the biotic/abiotic interface and controlled assembly, disassembly, and reassembly: This capability could enable a very wide array of new, tunable and responsive functionality and architectures. At the small scale, precisely constructed designer nanoparticles would improve a wide range of applications from energy conversion and storage to catalysis to navigation (e.g. magnetosomes). Ultimately these technologies could improve mobility and weight reduction, such as through devices that are more wearable or better integrated with the platform. Coordinated arrays of nanoparticles, or larger scale bioenabled structures, could provide autonomous sense and response to internal states (stress, fatigue, metabolic, pathogenic, etc.) and external states (environmental conditions, incoming threats, vibration/sound, etc.). Responses may include changes in optical/electromagnetic signature, mechanical, chemical, thermal, magnetic, pathogenic, and other properties. These materials, if living, might adapt and evolve rapidly to adjust to all external and internal conditions and regenerate as needed. There is potential in many of these capabilities to minimize the need for human interaction to enable and maintain integrated material performance. Smart, robust, evolvable materials could conceivably be developed that are adaptive, self-assembling, sensing, scalable, learning and communicating.

- Self-sustaining operation: Bio processes could enhance recycling to minimize user signature or environmental impact by enabling more effective waste-to-energy efforts and then using the degenerated chemical biproducts, and those from other materials scavenged onsite, to create new target materials. New biomaterials and their products could also improve water purification, a major world challenge in the coming years, including new approaches to desalination, heavy metal and radioactive particle removal, and other cleansing actions. Our approach to personal nutrition may be radically changed, from sensors that inform us about nutritional needs to meeting those needs through tailored or evolved biosynthetic pathways. As with sense-and-respond biocircuitry, many of these applications demand storage, transmission and stabilization of biotic-abiotic interfaces.

- There is significant opportunity to establish new paradigms in information management. Biological materials have the potential to generate, store and communicate complex nonlinear data. For example, using DNA-synthesis, where single nucleotide accuracy/resolution is not needed, portable archival storage of petabytes of data may be realized. There is a 'raw limit' of 1 exabyte/mm^3 (10^9 GB/mm^3), with an observed half-life of over 500 years, in these materials. Developing readout techniques is a key challenge. A possible way forward may be to structure the DNA-based data to enable logic strategies for pulling out specific pieces of data such as tags, indices and record keeping. The interface may also be developed outside of our current bounds of approaching this problem. Remotely brain-controlled, including thought controlled, interfaces may yield alternative modes of information transfer. Such capability is not inconceivable considering the current function of our own neural networks and their generation of and interaction with electromagnetic waves, and the wide availability of electrically and magnetically susceptible biomaterials.

Attendees:

Speakers:

Dr. Jeffrey Barrick (University of Texas, Austin), Dr. Mark Bathe (MIT), Dr. Keith Brown (Boston University), Dr. Moh El-Naggar (University of Southern California), Dr. Oleg Gang (Columbia University), Dr. Farren Isaacs (Yale University), Dr. Derk Joester (Northwestern University), Dr. Joel Kaar (University of Colorado), Dr. David Kisailus (University of California, Riverside), Dr. Ratneshwar Lal (University of California, San Diego), Dr. Larry Nagahara (Johns Hopkins University), Dr. Paras Prasad (SUNY-Buffalo), Dr. Nadrian Seeman (NYU), Dr. Christopher Voigt (MIT), Dr. Ting Xu (University of California, Berkeley), LTC Bull Holland (ARL-ARO Military Deputy)

Planning:

Dr. James Snyder (ARL-WMRD), Dr. Shashi Karna (ARL-WMRD ST), Dr. James Sumner (ARL-SEDD), Dr. Joshua Orlicki (ARL-WMRD), Dr. Charlene Mello

(NSRDEC), Dr. David Stepp (ARL-ARO), Dr. Dimitra Stratis-Cullum (ARL-SEDD)

Additional Participants and Observers:

Dr. Bryn Adams (ARL-SEDD), Dr. Robert Kokoska (ARL-ARO), Dr. Joseph Mait (ARL Chief Scientist), Ms. Pauline Smith (ASA/ALT), Dr. Christian Sund (ARL-SEDD), Dr. Abby West (ARL-WMRD), Dr. Jeffrey Zabinski (ARL-WMRD Director)

Vehicle-Based Soldier-Autonomy Teaming

December 6–7, 2016

Aberdeen Proving Ground MD

Organizers: Jason Metcalfe, Victor Paul, and Kaleb McDowell (ARL-HRED)

Introduction

> Even if we do not fight the producers of [these] sophisticated weapons, warfare will become more lethal as they export this advanced equipment to their surrogates or customers. Crises involving such adversaries will unfold rapidly, compressing decision cycles, and heightening the risks of miscalculation or escalation. Conflict will place a premium on speed of recognition, decision, assembly, and action. Ambiguous actors, intense information wars, and cutting-edge technologies will further confuse situational understanding and blur the distinctions between war and peace, combatant and noncombatant, friend and foe--perhaps even humans and machines. (Milley, 2016)

As illustrated by the above statement by General Milley, the future of armed conflict is expected to involve high tempo operations and engagements with increasingly sophisticated, near-peer adversaries that will threaten the U.S. military ability to achieve overmatch sufficient to maintain operational advantages. Conflicts are expected to unfold across distributed, multi-domain spaces that are unlike any previously encountered; unique operational challenges will emerge as a product of a complex mix of land, air, maritime, space and cyberspace based threats. Army teams will need to flexibly respond to challenges in this multi-domain battlespace whether in sparse rural or dense mega-city environments across a wide variety or terrain. Therefore, we may further anticipate operations to require adaptive vehicle-based Soldier-systems that possess a range of capabilities extending well beyond those existing in current and traditional military vehicles. Future Soldier-system concepts will be persistently influenced by evolving mission challenges (e.g., increasingly multi-cultural environments, ever-more advanced intelligent systems, dense and growing urban areas), constraints and requirements of specific operational approaches (e.g., distributed teams, reduced crew sizes, closed-hatch operations, Soldier-autonomy teaming), and the direction of technological advances (e.g., machine-augmented and intelligent agent enabled task execution, adaptive and individualized Soldier-system design).

It is recognized that combat vehicles are essential to successful operations and that modernizing through the integration of emerging technologies will provide significant advantages to win on future battlefields (ARCIC, 2015). To examine the role of future technologies in Army Combat Vehicles, ARLs Center for Adaptive Soldier Technologies hosted an Army Science Planning and Strategy Meeting (ASPSM) on the topic of “Vehicle-based Soldier-Autonomy Teaming” in December, 2016. Over the course of two days, scientists and engineers from Army research and development organizations (ARL, TARDEC) met with domain experts from industry and academia to examine critical issues facing future Soldier-autonomy team operations, envision operational Soldier-autonomy interactions in future battlespaces, and identify key capabilities to be enabled through manned vehicle-based Soldier systems. The group analyzed the identified capabilities to derive concepts of future Soldier-autonomy teams and fundamental research required to enable their realization.

The first day of the meeting began with a brief set of overview and context presentations to define the problem space as that of enhancing the interaction of Soldiers with advanced systems through concepts of teaming. More precisely, the objective was to deeply assess the challenges involved in seamlessly integrating advanced (and evolving) vehicle-based autonomy, as well as enabling technologies, with Soldiers in such a way as to account for mission dynamics, individual variability among teams, and intrinsic state changes within individual Soldiers through all stages of mission planning and execution. Following the opening session, the participants were assigned to three different focus groups and each were given a general operational context to frame their consideration of critical future capabilities. The focal scenarios were described as “leader interaction in a rural environment”, “presence patrol in a low-density urban environment”, and “extraction in a megacity environment”. The focus groups were asked to brainstorm potential future capabilities for manned-unmanned teams. For each identified capability, the groups discussed the risks and rewards that the capabilities addressed, why they believed the capability may succeed, what would prevent the success of the capability, and finally, the general timeframe (mid (2025-2035), far (2035-2050), and futuristic (beyond 2050)), which its maturation would be expected. The first day concluded with all focus groups reconvening and sharing the sets of capabilities that were identified. Overnight, the identified capabilities were compiled into a single document and disseminated to all meeting participants. For the second day of the meeting, the participants were then self-organized into four different focus groups, two that were asked to identify fundamental scientific research that was required to bring the capabilities to fruition and two that were asked to define operationally-situated concepts within which the various capabilities would be applied.

Capabilities for Future Vehicle-Based Soldier-Autonomy Teaming

In total, the three focus groups identified 37 future capabilities, many of which appeared to have common notional underpinnings. Four of the capabilities were identified with descriptive titles, but not as fully specified as the rest. Of the identified capabilities, the overwhelming majority (22) were labeled as either mid or mid-to-far, 7 were identified as either far or far-to-futuristic, 3 were considered futuristic, and the 5 were not given a timeframe (though 4 of those 5 were the capabilities that were not defined in detail). In the following we present the capabilities as identified by each of the focus groups, organized by timeframe for capability maturation. Interestingly, the group that was focused on a leader interaction in a rural environment mainly identified capabilities on a mid or mid-to-far horizon whereas the other two focus groups identified, in near equal proportions, either mid-term or far/futuristic capabilities with few in between (mid-to-far).

Across the discussions, a strong theme emerged that interface technologies, comprised of sets of intelligent agents, hereafter referred to as intelligent crewstations, will be critical to "team" with Soldiers while executing all phases of operations. Advancing technologies for intelligent crewstations will enable mission planning, execution, dynamic adjustment, and after-action review for improved training. Moreover, this foundational intelligent crewstation-Soldier team will provide an essential functional unit to enable manned vehicles to team with other manned and unmanned assets to maintain survivability and lethality during mobile operations across a range of environments. In addition to the intelligent crewstation theme, several other strong themes of future capabilities also emerged from the meeting:

- Intelligent Soldier aides for operational training, mission planning, and rehearsal
- Effective real-time maintenance and communication of situational awareness across Soldier-autonomy teams resilient to degraded, compromised, and rapidly-changing informational conditions
- Situation-adaptive reasoning, dynamic resource allocation, and task management to support collaborative Solider-autonomy decision making and performance
- Context and state-aware autonomy to detect or anticipate operational needs and take necessary actions to support the Soldier-squad mission

- Heterogeneous unit teaming including direct interactions across mounted, dismounted, and unmanned assets that function robustly across the information and capability divides between platform-specific mounted and dismounted technologies.

Intelligent Soldier Aides for Operational Training, Mission Planning and Rehearsal

- <u>Re-define or revised Army hierarchy that includes non-human agents</u> Identify role of different automations and artificial agents within a relevant military command structure

- <u>Intelligent interface for Army battle command and analysis</u> Provide an accurate real-time operating picture by leveraging pre-mission data as well as dynamic intelligence gathering for improved situational awareness and team facilitation through asset monitoring and management.

- <u>Virtual-reality based mission interactive briefing</u> Human-interactive virtual or augmented-reality based briefing that leverages artificial intelligence, with minimal human input, to generate situation-specific scenarios that integrate knowledge of cultural norms (e.g. common body language, local idioms) and other mission-critical data. Enabled by logging capabilities of multimodal, immersive interfaces, may later sub-serve after-action reviews and scenario-based trainings

- <u>Individualized performance assessment</u> Provide Soldiers individualized assessment and feedback regarding their current suitability or readiness for a given mission based on their state, knowledge, skills, and abilities.

- <u>Active development of team trust</u> Considered broadly, trust between agents includes human-human trust as well as human-nonhuman agents in teams. Implicit is the involvement of all team agents in training and learning scenarios to build a baseline level of ambient “team trust”, but also to consider structuring team dynamics to enable and support active trust management schemes when embedded in operational tasks and contexts.

- <u>Adaptive training agent</u> Specifically, tracks attention in the user as well as confusion, and can pause, repeat, and attempt to clarify details that the user doesn't understand. Allows condensation of details that the user's profile/background suggests they already know and emphasis on known areas of opportunity in their skillset.

Real-time, Resilient, and Distributed Situational Awareness

- Immersive, multimodal interface Leverage multiple human sensory modalities (e.g. auditory, tactile) to deliver information to team about their upcoming mission, such as data regarding culture, environment, mission, goal, team capabilities, vehicle state, team members state (physiology, psychology). Intelligent, innovative use of space and surfaces in vehicle to communicate (in addition to HUD or screen).

- Multi-modal, agent-based intelligent sensor network Distributed system of permanent and/or semi-permanent, agent-borne (Soldier, vehicle), sensors for real-time sensing and archival access. Multi-layered to include physiological and environmental monitoring as well as higher-level inference such as tracking socio-cultural variables of interest.

- On-vehicle data processing and sensor fusion To provide real-time and on-demand information to support real-time situational awareness and aided decision making.

- Adaptive and intelligent inter-vehicle connectivity Use of pre-loaded and local transmission between vehicles to enable robustness in coms, sensor feeds, and other data transmission to maintain local function that is external to and not completely reliant on a larger battlefield or urban network.

- Natural language-based awareness Comprehensive, adaptive natural language component for machine control and for augmenting human understanding and decision making. Comprehensive means that, as a sensed component and as a command input, it can incorporate gestures, expressions, tones as well as how they vary according to the context (socio-cultural, operational, based on the internal state of the communicator).

- Context-aware HUD HUD is customized based on user context as determined by intelligent agent, mission parameters, current user physio status, and direct commands. Commands can include gaze tracking, gaze-zoom, brain control, wrist-worn

Situation-Adaptive Reasoning for Dynamic Resource Allocation and Task Management

- Confidence-based inference of team intention Computational identification and classification of individual and group intention for both opposing and friendly force with integrated confidence on sensor data, state estimates, and the intention predictor.

- Human state management Application of proven techniques to influence and modify human physiological and cognitive states.

- Automated contextual and situational recognition Specifically for the generation of appropriate smart alerts, queries, imperatives, or to enable a system to take autonomous action.

- Dynamic system adaptation and reconfiguration Enabled by an adaptive learning system to respond to nonlinear changes, such as big structural changes in the team or its assets while preserving a recognizable command structure. Both software (e.g. algorithms, sensor management) and hardware (e.g. reconfiguration, replacement) to account for partial or total instrument or agent failure or loss.

- Leverage and adapt existing environment To act on, engage with, and modify a given environment through small teams of man and unmanned assets that are able to jointly exploit the environmental affordances, both implied and by mechanical design, to augment team and compensate for capability gaps in the service of current mission needs and overall objectives.

- Iterative human-machine problem solving Enable humans and non-human agents to engage in iterative, joint problem solving that will enable faster and more robust solutions; leveraging human adaptability and thinking outside of rule-bound structures while capitalizing on rapid computational reasoning and scenario analysis of intelligent, computationally augmented agents.

- Dynamic load and task management Leverage team and individual state inference to detect circumstances of overload or potential overload and dynamically re-allocate tasks and roles to compensate. Enable tiered strategies to allow provision of the least help that is necessary and sufficient to mitigate overload (whether provision of information or complete re-tasking).

Squad State and Context-Aware Autonomy for Mounted and Dismounted Mission Support

- Autonomous commandeering Enables leveraging of existing urban infrastructure, information, and mobility networks to enable achievement of mission and provide physical and information security.

- Autonomous dismount support Dismount-support system that autonomously can provide medical care and security through active defense and shielding.

- Autonomous asset placement and management System to enable dynamic physical support of dismount forces by increasing efficiency in placement and accessibility of operational assets.

- Vehicle-mounted multi-UAV operation center Individual docking ports for approximately 5 UAVs enabling optionally-autonomous launch, control, and renewal. An intelligent control system should be integrated with the vehicle to enable autonomous coordination of the UAV group, including monitoring for self-refuel and repair (leveraging a 3D printer and robotic assembly kit). Enables as-needed handoff between the vehicle-based controller and mounted- or dismounted-Soldiers, leveraging physiology-based sensing to enable Soldier state-based semi-automated handoff (e.g. during high stress/overload conditions, system can determine high-level functions such as “follow”, “return home”, etc).

- Medical evacuation for patrolling teams. Vehicle deploys flat autonomous stretcher for personnel retrieval that contains containment gel and more advanced status monitoring. Upon arrival, system wraps wounded combatant in a super-cooling stasis gel to limit the risk of battlefield bleeding fatality. The structure of the system can then monitor, assess, and transport the wounded warfighter, either to the deploying vehicle to a pick-up point for an autonomous quadrotor device.

- Proactive, predictive action Using the most salient factors and models of likely scenarios, perform reasoning and anticipate behaviors most necessary to perform to optimize survivability and mission success.

True Heterogeneous Teaming, Robust to Information and Capability Divides

- Human-directable automation Advanced automation that is designed to enable human interactions that allow directing and influencing function to flexibly achieve desired outcomes.

- Automated task management system Adaptable system to prioritize and share tasks within and among teams of human and machine teammates.

- Human-automation-integrated team facilitation To integrate all agents in a mission using a cohesive framework for clear, concise communication, information transmission, and problem-solving that is tailored to the needs of each individual agents state and experience as well as defined military command structure.

- Optimized human-machine decision making Autonomy capable of perceiving the physical, psychological, and social state of the crew (to include defined operational hierarchy), including individual knowledge, preferences, and intent and then, in turn, tailor the level, cadence, and other aspects of information transmission to optimize the crew's situational awareness and decision making as well as to tune the response of the autonomy to the crew and context.

- On-board intelligent action in high uncertainty Enables operation without network connectivity and/or with greatly degraded information quality and team capability.

- On Board Intelligent Assistant Leveraging on-vehicle processing and multi sensor fusion, intelligent (automated) task management and prioritization algorithms enable a rich, multi-modal human machine interactive system that provides for faster, more effective decision making, offloading of cognitive tasks and enables shared situational awareness.

Fundamental Research to Enable Future Capabilities

Fundamental research was identified that will be required to enable the realization of future Soldier-autonomy team capabilities. Several of the most critical research questions cut across major capability themes identified above:

Human State Characterization: There is a need for better ways of characterizing human state (cognitive/affective/social) in ways that are useful to and usable by (i.e., that can be reasoned about) by autonomy and other human to facilitate mutually-adaptive teams. Underlying this general requirement are research needs including: understanding variability across and within humans; understanding the limits and the opportunities for new mathematical methods to address real-world levels of complexity with potentially unstructured and incompletely characterized state space; and understanding the relationships between sensing (characteristics and performance properties under operational conditions) and human state estimation biases and variability across multiple modalities and scales.

Enhanced Communication between Humans and Machines: There is a need to develop better approaches to exploit human multisensory capabilities and share concepts for effective communications between humans and machines. Underlying this requirement are research needs including: cross-modal approaches to enabling real-time human comprehension under constraints of bandwidth, information quality, and task; predicting the effects of individual Soldier variability in sensory perception and utilization, as well as, the effects of variability arising from operational/technological factors (such as clothing, headsets, crewstations) on the ability to comprehend information; and developing approaches to share concepts across the information and capability divides of platform specific manned, unmanned, and dismount technologies.

Linking Individuals to Team Behavior: There is a need to understand the mutual influence and adaptations between individual and team behavior. How does an individual impact team behavior and how does team behavior impact the individual? Teaming is not about boxes and functionality, it is about interdependence among the boxes. Accounting for interdependence requires observability, predictability, and directability. Perception and adaptability provide feedback among these three elements and define research requirements including: develop the interface between observability and predictability; understand how a transaction between humans and intelligent systems occurs; develop tools that help identify parameters critical in collaborative behavior; develop tools to understand the psycho-physiology of intelligent systems and hybrid teams; and develop meaningful measures to assess team behavior.

Robust Human-Autonomy Integration: There is a need to understand approaches to match human capabilities with the capabilities of rapidly advancing autonomies. Underlying this general requirement are research needs including: identifying the critical attributes of agents that would successfully integrate in the crew-automation environment; understanding human-autonomy integration in terms of recruitment, assembly of teams, understanding how to establish training protocols and potential removal from service or prevention of inclusion; developing novel approaches to integrating humans and autonomy focusing on non-traditional tasking and decision making processes; principles to develop an adaptable user interface to facilitate tuning to individual variability (biases, proclivities, capabilities); principles and ethics underlying the generation, evaluation, and refinement of adequate mission plans for distributed human-autonomy teams. There is a need to define the kind of assumptions can and should be made considering long-term societal shifts in the relationship between humans and automations, taking into account anticipated perfusion of sensor, computational, and control technologies throughout daily life.

Human-Autonomy Teaming Analysis: There is a need develop the requirements for tools to help design and build human-machine systems? We have tools to analyze automation and we have tools to analyze human performance; however, analyzing teams of humans and intelligent systems is not a linear combination of these two and the current methods and approaches to analyzing heterogeneous teams of humans and autonomous agents remains deficient. Underlying this requirement are research needs including: developing system engineering practice and models to: better integrate the human, account for dynamics of work, team, individuals, environment, better account for the concept of time, present alternatives, and critically, account for intelligent systems working collaboratively with humans. Further sufficient optimality criteria need to be defined, implemented with appropriate metrics for human-autonomy team success.

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Materials for Sustainable and Mission Flexible Intelligent Systems

December 8–9, 2016

Aberdeen Proving Ground MD

Organizers: Dr. Shawn M. Walsh (ARL/WMRD), Dr. William L. Benard (ARL/SEDD), and Dr. Ivan C. Lee (ARL/SEDD)

Speakers: Preference was given to maximizing input of *all* attendees, and minimizing "seminar" style presentations. As such, only five speakers were invited to present, and they were chosen primarily as active representatives of the three key themes that defined the bounds and scope of the ASPSM meeting:

- Robust Self-Sustainment in Austere Environments - Enablers for Comprehensive Power and Energy Efficiencies – *Professor Dionisios Vlachos, University of Delaware*
- Actuation and Maneuver as a Fundamental Materials Challenge - *Professor Rob Shepherd, Cornell University*
- New Synthesis and Process Enablers for Multifunctional Power, Mass, and Volume Efficiencies - *Professor Michael McAlpine, University of Minnesota*
- ARL Intelligent Systems Vision for 2030+, *Dr. Brett Piekarski, ARL*
- Soldier Users Community Perspective on the Potential and Current Limits of Unmanned Systems, *Mr. Keith Singleton, Chief, Unmanned Systems Team, Maneuver Battle Lab, Fort Benning, Georgia.*

Background:

On December 8th and 9th, 2016, ARL hosted an Army Science Planning and Strategy Meeting (ASPSM) on "Materials for Sustainable and Mission Flexible Intelligent Systems." The meeting was based in part on the hypothesis that integrated innovation in materials, synthesis, and energy have a fundamental role to play in disruptively advancing desirable and necessary intelligent platform capabilities and behaviors over a range of moderate to extreme operating conditions. However, this hypothesis also maintains that advances in "classical" materials, synthesis, and energy may not be sufficiently capable of expanding beyond their own inherent limitations without new and meaningful connectivity to other, perhaps disparate, physics, chemistry, biology, and computation phenomena. *Every* ASPSM invitee is a noted pioneer in fields and activities related directly and indirectly to the ASPSM meeting; indeed, it was the significance of their professional accomplishments to date that made them especially critical to helping define where the current gaps – and opportunities – lay in this area. The goal of the ASPSM meeting was to create a conversation that would allow for materials, synthesis, and energy to be discussed explicitly and simultaneously in the unique context of intelligent systems. Mass, volume, and energy efficient bounds defined the fertile space for identifying the knowledge gaps and transdiscipline work that needs to be done so that offsets in intelligent platform performance could be assured deep into the Army's future.

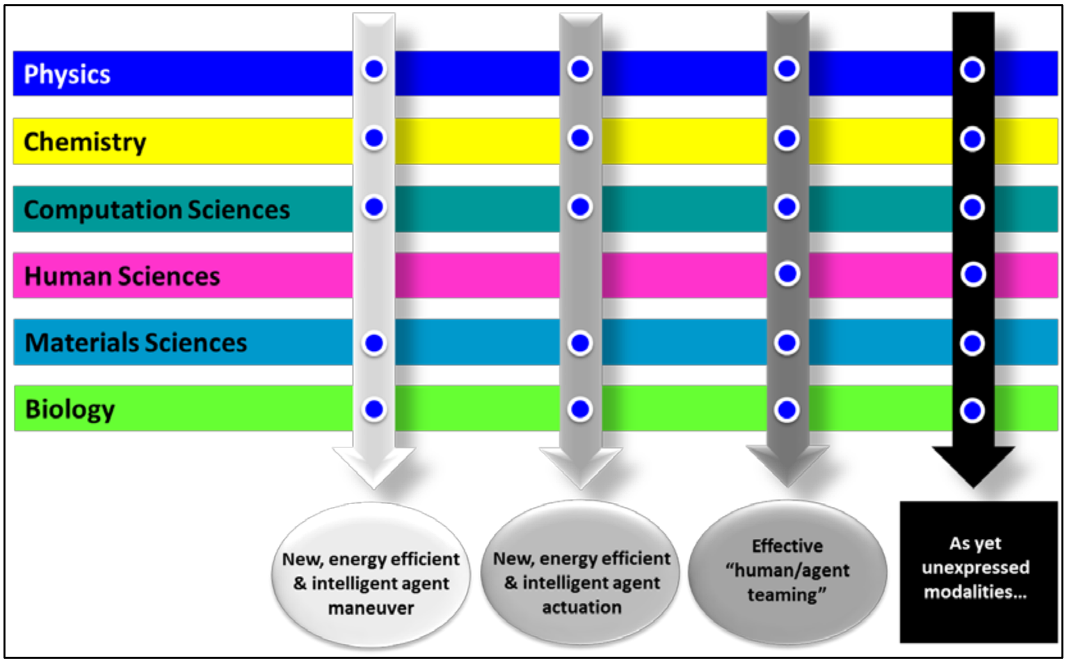

Figure 1. Army Science Planning and Strategy Meeting Goal: Attempt to promote transdisciplinary thinking as it relates to intelligent systems and robotics

Objective & Scope:

To date, research in robotics and autonomous systems has been driven by the "hard problems" associated with advances in greater (and true) autonomy, artificial intelligence and device control, sensor development and data fusion, object recognition and navigation, multi-agent coordination, and human-machine interfacing, training, and teaming, among others. Concomitant with these thrusts has been pioneering research conducted from a materials, synthesis, and energy perspective, and highly novel intelligent system behaviors and performance characteristics have been demonstrated with varying levels of success and technological maturity. However, although some energy efficient "behaviors" have been identified (including those imitated synthetically or mechanically from nature), many of these material concepts have been developed with little or no bounds on mass, volume, and energy efficiency – or if they have, the bounds have been rarely comprehensive. Some of these bounds are shown in Figure 2. This ASPSM meeting challenged participants to think of the “penalties” associated with achieving desired intelligent system and platform capabilities *upfront*, so that fundamental research opportunities and knowledge gaps could be identified to break through limitations on current platform performance (e.g., mission endurance, durability, maneuver and actuation in extreme terrain and airspace, etc.)

Challenges:

- Operate in austere environments (e.g., limited energy sources/options)
- Operate in logistically limited/denied environments
- Operate in difficult mobility/maneuver environments (e.g., irregular terrain, extreme weather, subterranean and dense urban environments)
- Operate in environments where excessive noise can compromise Soldier and the mission
- Minimize weight burden to human Soldier
- Rapidly adapt functionality to enable mission-needed capability

Figure 2. Identifying the Bounds on Performance of Intelligent Systems to Inform Fundamental Research and Knowledge Gaps

Equally important however is identifying how fundamental advances in materials, synthesis, and energy could enable entirely new modes of intelligent system capability, behaviors, and responses on different length and time scales. For example, prior ASPSM meetings cited “resiliency” as critical in both individual and multi-agent systems (e.g., swarms, flocks, fleets). New and comprehensive approaches to materials and energy could span the spectrum – from enabling radically “attritable” systems to developing new and complex behaviors that give disruptive strategic and tactical advantages in Soldier/robot training and teaming. These advances not only are strategic from a military perspective; they also have the potential to dramatically expand competitive advantages in the commercial sector use of robotics and intelligent systems. As such, new insights and invention in this area could be equally vital to both U.S. economic growth and the ability to domestically and rapidly manufacture DoD-critical materiel – including sustainable and mission flexible intelligent systems.

It is worth defining “intelligent system” for the purposes of this ASPSM meeting given the broad lexicon and available terms commonly used (e.g., robots, autonomous systems, semi-autonomous systems, unmanned platforms, optionally manned platforms, drones, intelligent agents and systems, etc.) While the ASPSM discussions, insights, outcomes, and recommendations could be applicable to a richer cross-section of robotics (e.g., discrete platforms, human-machine interfaces, powered exoskeletons, and industrial robotics) the scope was primarily bounded by the desire to address knowledge gaps and critical limitations on air and ground intelligent systems. As such, a working definition for "intelligent systems" for this meeting was: devices for the remote projection of a desired capability with levels of decision-making ranging from total human control to total device autonomy.

ASPSM Day 1 Meeting Strategy

The first day of the meeting began with immediate and unstructured engagement of all invited participants. All participants – to include those from academia, industry, other government laboratories, and the Army Research Laboratory and Army Research Office – were asked to describe their "hardest problem" – that is, what they would like to do, but cannot at this time. The only constraint was that the participants attempt to link their hardest problems to one or more of the three key workshop themes:

- Robust Self-Sustainment in Austere Environments – Enablers for Comprehensive Power and Energy Efficiencies
- Actuation and Maneuver as a Fundamental Materials Challenge
- New Synthesis and Process Enablers for Multifunctional Power, Mass, and Volume Efficiencies

This round table discussion was then followed by aforementioned invited presentations. Since we had a diverse set of invited participants who may not have depth in all three key theme areas, these presentations helped provide context. The audience was encouraged to ask questions of all speakers to provide first-hand access to the academic and the two extreme ends of the Army "intelligent system" spectrum (i.e., R&D and User Community).

A very candid sampling of the "hard problems" and shared insights transcribed from notes and output recorded during the informal engagement with ASPSM attendees over the two day meeting include:

"I think it is important for us to expand our knowledge of the dynamics of materials properties, especially mechanical, in the context of energy storage, energy release at high rates, and shape and structure transformations."

"Power and propulsion are key. Without them, robots are going nowhere fast, and [will be of] limited strategic value. Strap a jet engine to a brick – and you've got

some very real capability. How do [we as a research community] advance intelligent system propulsion and power?

"Soldiers often have to carry everything they need like armor, batteries, ammunition, water, and now, some [man-portable] robots into [remote] locations. Remember that. That is why reducing weight [of these items] is so important for Soldiers and key to [Army User Community] acceptance of new technologies"

"There is a trend [in the research funding agencies] to mandate modeling, roadmaps, "tool development", etc. in proposals for research in areas like this. Those may only lead to lots of information on inferior concepts or materials etc. More room is needed for exploration. Models and tools will flow better and be more useful after discovery…breathing room for new insights and discovery is needed."

"[We can already] dramatically shift elastic [monolithic] material moduli now. But so what? What useful bulk properties or useful [robotic] response has that really given us? Maybe some useful [applications] in soft robotics. We need to think well beyond pure material property development, and maybe do it in [context] of unprecedented morphologies and multiscale materials mechanisms to give us breakthrough response times and levels of actuation force that we just don't have right now."

"My 'hardest problem' is a cultural one [in robotics research]. How do we work basic science and engineering together, with people right across the hall [at my university]?"

"We have tools we didn't have 10 or 20 years ago. Additive manufacturing may be at risk of being oversold, but really we are at the dawn of this type of capability. We can and will continue to achieve absurd complexity that can enable [entirely new] approaches to [intelligent system] design, materials and power. [Synthesis] and manufacturing could be the nexus of many of the advances we are talking about [at this meeting].

"I could not help notice that the line between "smart materials" and "robotic materials" becomes very, very thin in some areas. [But] it does seem like there are clear distinctions and linkages, especially in reflecting the local and global intelligent system needs and required capabilities."

"[Simply developing tools and research for] mimicking nature is a waste of time for robotics. Nature isn't always that efficient at everything, but it is often good over a range [of behaviors and phenomena]. [The key is] being inspired by nature to identify the [complex] approaches used to achieve efficient material and energy use and adaptivity in the environment where [living organisms] live and flourish."

“One take away from the meeting that struck me was that, since the field is evolving and highly interdisciplinary, it seems to be lacking basic understanding of physical constraints. I said as much during the wrap up sessions. I was shocked that some argued that solar energy could supply the needs of advanced robotics, and they dismissed higher energy density mechanisms. It was very telling…..But I found that some in the audience were unable to understand concepts like energy and power density. This is a huge limitation to advancing the field.”

“We need to distinguish what we mean by “computation” and “analytics.” Both are important to robotics as [intelligent systems] evolve. Also bringing computation and control into the materials to [enable them to] shift properties or morphologies on different length scales – that’s an exciting place to be if we want new [approaches] to materials and energy use [in intelligent systems].”

“[There is] a joke from the comedian Mitch Hedberg: “An escalator can never break: it can only become stairs. You should never see an Escalator Temporarily Out Of Order sign, just Escalator Temporarily Stairs. Sorry for the convenience.” [He] definitely [has] the right idea. If you can have a device that has one very useful behavior when it’s powered, and another useful behavior when it’s not powered, that could be powerful in the design of systems in which power is limited. You could think about intentionally staying in the “no power” mode even when you have power, to conserve for when you really need it.”

Day 1 Breakout Session Strategy

The afternoon, and the bulk of Day 1, was devoted to breakout sessions that were focused on the three key ASPSM theme areas.

Orange Team: Robust Self-Sustainment in Austere Environments – Enablers for Comprehensive Power and Energy Efficiencies

Yellow Team: Actuation and Maneuver as a Fundamental Materials Challenge

Green Team: New Synthesis and Process Enablers for Multifunctional Power, Mass, and Volume Efficiencies

“5+2” Breakout Session Brainstorm Questions: All participants were given a set of 5 predetermined questions to use as basis for brainstorming. They were also asked to develop 2 “new” additional questions. Finally, they were encouraged to replace any of the 7 (“5+2”) questions in favor of ones they felt were more provocative and effective. The only constraint imposed was that each session remain faithful to the theme of the breakout session to which they were assigned, but outcomes could definitely link to other theme areas outside their breakout session. ASPSM organizers served as facilitators for each of the breakout sessions.

1. What are the fundamental properties of robust actuation materials (robust in terms of operational environment and performance)?
2. What are the key elements of holistic energy efficient actuation (mechanism scalability, match to desired effect, self-sustainment)?
3. What are the physical performance bounds?
   - Mass
   - Energy Density
   - Idling Penalties
   - Operational Environment
   - Maneuver
4. How do we balance complexity of synthesis/assembly with performance?
5. How do we balance mission specific performance with robustness?

Day 2 Session Strategy

After reconvening on Day 2, the ideas developed from Day 1 breakout sessions were discussed in more detail as an entire group. The goal was to begin to identify common themes, group them where it made sense, and provide more cohesive and succinct research recommendations. The caveat was to remain faithful to the three themes that defined the unique scope of this ASPSM meeting, and to use the Day 1 breakout session outcomes as a basis for expansion and refinement of knowledge gaps descriptions. Hence, although the three workshop themes are implicit in all of the outcomes below, it made more sense to provide new titles that better describe the *cumulative* insights and areas identified by the breakout session groups and individuals alike.

- **Upsetting the Autonomous Applecart: New Modes of Mobility, Actuation, and Manipulation**

Roboticists are already actively exploring and addressing the problems of motion and actuation from a physics standpoint, as well as making the linkages to other elements (e.g., design, power, computation, materials, etc.) to develop functional systems. For example, the term *robophysics*[1] is well suited to describe the overall framework for many of the areas discussed in the ASPSM meeting – including the "intersection of robotics, soft matter, and dynamical systems[1]." Indeed, the Army has funded and supported such efforts[2] across a variety of internal and external research efforts, and collaborations with academia and industry. Many of the

ASPSM participants have pioneered not only terms like “robophysics” and “robot blood[3]” but also have been part of efforts to more comprehensively inform intelligent systems capability through interdisciplinary science and technology integration. However, the goal of this meeting was to identify the gaps and challenges that preclude further advances in this space, as well as the opportunities that may now be possible. Some key insights from breakout sessions include:

- Currently, there is heavy reliance on very conventional, inefficient, and power hungry electromechanical systems for enabling locomotion and actuation. Many of the innovations are achieving complex behaviors (snake-like mobility through confined spaces, adaptivity to solid and granular surfaces, soft, conformal gripping of objects, adaptive aerofoils for low power loitering). Much of the integration is still conducted at the macro level – and not addressed as a more fundamental material or true multifunctional materials problem

- Achieving reliable and repeatable levels of desirable motion, mobility, and manipulation rapidly becomes challenging as the length scales become finer and the devices become smaller. Yet nature seems to operate just fine (e.g., insects) on smaller length scales, as well as in the face wind, rain, and other adverse and unpredictable environmental influences.

- With notable exceptions many roboticists (and robophysicists) designing and synthesizing robots are using materials that are fairly conventional, if not “commercial off the shelf” or antique. Conversely, and more importantly, they [roboticists] are not always fully aware of what materials and energy expertise can bring. The idea of “kits” was suggested – to allow materials scientists to supply or tune materials unique to robotics applications. Earlier transdisciplinary research connectivity is equally important, so that robotic modes and materials could be conceived in tandem. There is significant value in bridging the Robotics Community with the Materials and Energy communities. Historically, the Robotics community has focused on mechanisms and algorithms to demonstrate concepts. Advertising the full capability of new materials and energy systems both in terms of properties, as well as access and design rules for synthesis, could lead to new breakthroughs. Ideally a library of materials and mechanisms for actuation would be developed – to enable a dialog between materials scientists and robotics community to find better materials and multifunctional responses.

- Absent in many of the approaches towards locomotion and actuation in intelligent systems and robotic devices are alternative approaches to energy and power – including *a priori* assessment of the energy penalties for achieving performance. There is not a cohesive or fundamental approach for enabling much higher energy densities in the context of robotics. There is a gap in (and need for) more direct and efficient energy conversion mechanisms to enable actuation, locomotion and manipulation. Specifically, there is a gap in developing materials that could support new modes of intelligent, energy-dense and efficient actuation (e.g., materials to contain caustic chemical reactions for energy conversion, micro-combustion, materials for flexible, multifunctional fuel cells, multisource energy harvesting, etc.)

- There is a gap in developing distributed control within materials and structures, and a need for concurrent and holistic design of structures and materials.
- Develop combinations of both materials and energy fields to enable actuation and manipulation. The use of fields to change states of matter is not new. But the relatively weak, sloppy, or power intensive nature of "conventional" approaches (e.g., electrorheological fluids, magnetorheological fluids) often make them impractical and confined to a lab bench novelty. If materials could be designed in such a way as to allow for rapid and reversible changes in properties (e.g., load bearing "switches" made in the material itself that could be readily realigned from one state to another by strategically applied fields or energy) it would be an enabling benefit to actuation and dexterous manipulation. The goal would be a more adaptive, energizable version of a "universal gripper" by thinking deeper about the morphologies of the materials, and how the particles or substructures can align or disperse with localized and controlled application of fields (pressure, vacuum, electric, magnetic, etc.)
- Vastly improve the ability of organic and inorganic materials to store and release mechanical energy; new tools and concepts to manipulate the complex moduli of materials.
- Engineer materials so they can be readily broken down and reassembled with minimal energy required to move from one state to another –and then back to the original state (highly reversible, with little or no loss).
- Noise and excessive heat generated by robotics systems are often afterthoughts and may be acceptable for, say, manufacturing robots. But for the Army, such operating artifacts of intelligent systems could compromise a Soldier or the mission because these artifacts are easily detected. Early

and fundamental consideration of noise and heat generation *as a materials and energy problem* in the context of intelligent system mobility and actuation is warranted, and as evidenced in the recent Marine's dismissal of a "Big Dog" variants due to noise, it is a current gap[4].

- Robot performance is fundamentally limited by the availability of conventional bulk materials to convert, store, and release energy[5]. For example, robot performance is limited by the power density of actuator materials and locomotion stability can depend on the passive dynamic properties of structures such as legs and feet. Current bulk materials are not matched to the performance needs of robots; for example piezoceramic actuators have very low strain while dielectric elastomers actuators have high damping due to fundamental material properties. By constructing metamaterials at the nano, micro, or milliscale, novel mechanical and physical properties could be incorporated into individual ``domains". By organizing 2D and 3D arrangements of these domains, novel properties could in principle be preserved in bulk metamaterials, and appropriately scale. Example metamaterials for robotics could include transducers which convert fields to mechanical energy, thermal to mechanical energy, or convert chemical to mechanical energy. Other metamaterials could have mechanical properties such as stiffness or damping which are easily tunable on demand, either at fabrication time, in the field, or dynamically while in operation. Research is needed into understanding the physics, design, and fabrication of these proposed metamaterials.

- While a strong and sensible case can be made for moving away from discrete and fairly conventional devices and mechanisms to purely material-based actuation, there are knowledge gaps and current bounds on performance that limit this desired capability. These include the ability of so-called "smart materials" to generate any significant amounts of force to enable an equally significant amount of work. Also, the responsiveness of many materials to imposed stimulus is not robust or adequate. The materials might be very responsive upon stimulation to shift from one state to another, but they are often unacceptably slow in reverting back to their prior state. This is a serious limitation, as mentioned earlier from a materials perspective. Truly reversible and responsive materials and energy coupling is needed. Responsive materials coupled with responsive structures enabled by low power to generate globally responsive macrostructures; and reconfiguring the dynamics and kinematic properties of the materials, are current gaps.

- How do we inform the hierarchy of actuators, sensors, energy, and structures to "turn on" and "turn off" at their optimal length and/or time scales?
- Materials that retain their extreme "stretchability" and elasticity over extreme temperature ranges are highly desirable and elusive currently (e.g., 10% strain, >400ºC)
- High Efficiency Chemo-Mechanical Actuation: Leverage extraordinary energy density of chemical fuels and materials: develop tools to process efficiently into motion; develop architectures for scalable robust actuation; "robot blood" distribution and caching of energy

- **Beyond Additive Manufacturing: Multiscale Synthesis, Processing, and Fabrication of Material and Energy Management Infrastructure Unique to Intelligent System Needs**
  - Gaps exist in achieving multimaterial integration on different length scales, and this multimaterial integration should be expanded to include materials used as energy sources, computation, and local and global sensing. Current synthesis, processing, fabrication, and manufacturing science offers hope, but these areas are often an afterthought in the current robotics community. A truly holistic approach, across design tools, materials, energy, and robotic science is needed. We can fabricate morphologies and structures and components on different length scales that we have never been able to before; so why aren't we?
  - A serious gap exists in the quality, complexity, and true multifunctional of materials and components that can be additively manufactured by current synthesis and fabrication methods. A novel alternative would be to explore much more aggressive innovation in the type of materials and subscale/microscale components that are fed into these additive processes. These materials could be "engineered packets" that contain structural, computational, sensing, and power elements. They could be metamaterials, multifunctional materials, energy dense materials, and even robot blood. These "robopackets" could be fundamentally designed in such a way as to allow for rapidly configuring *and* reconfiguring them into new and desired components for the intelligent system or robot. It would also be necessary for these packets to be readily disassembled. Rapid disassembly of materials is a neglected knowledge gap in processing. Disassembly of finite robotic materials would enable them to be repurposed in new and needed structures required by the robot or intelligent system. There is, currently, very heavy

emphasis on "additive manufacturing" but it would be desirable to have a fabrication process that is capable of *both additive and subtractive* influence on materials – including the robopackets. Thus, *simultaneous* innovation in the development of both the robotpacket concept and the additive and subtractive process concept could provide entirely new means to efficiently achieve hitherto unavailable complexity in bulk material and component response for the intelligent system.

    - Many current methods for synthesis (from chemical scale to additive manufacturing) do not get below defect densities sufficiently or reliably. Eliminating defects is a limit in general on processing, but also key to ensuring more reliable and complex material response for intelligent systems.
    - Microrobotics have a significant role to play in enabling new modes of macro-system capability and manufacturing and processing of materials, and would benefit from advances in more efficient materials, power, and control for actuation on very small length scales. Microrobotics also have the ability to reconfigure fixed amount of materials and energy resources to enable the needs of the larger, global, "macro" robot or intelligent system. And microrobots could be dispatched to bring back material and energy resources from the operating environment (drone/worker bee analog)
    - Though early, it is possible to "print" and "reprint" materials and custom infrastructure directly on the human body. What new benefits does that open up for improving human-machine interfacing and teaming?

- **Eat Out or Dine In? Expanding the Menu Options for Efficiently Feeding & Sustaining Intelligent Systems in Austere Operational Environments**
    - The lack of a comprehensive approach to energy and power storage, generation, acquisition, and strategic management and use in the context of intelligent systems was consistently identified by all breakout groups as a critical knowledge gap. Energy is precious and critical for intelligent systems to exhibit decisive and swift execution of tasks and maneuver. Gaps exists in the development and integration of (1) multifunctional materials for better energy storage, (2) material and morphologies for energy and power "infrastructure" (3) intelligent local and global energy management in the intelligent system; (4) expeditionary and environmental energy acquisition and replenishment; (5) situational awareness, tools, and data integration for *apriori mapping and assessing* available energy resources in the mission operating environments (e.g., natural materials or man-made

(power lines, fuel depots, waste, scrap, etc.)). A first attempt to schematically present some of these ideas and relationships is shown in Figure 3.

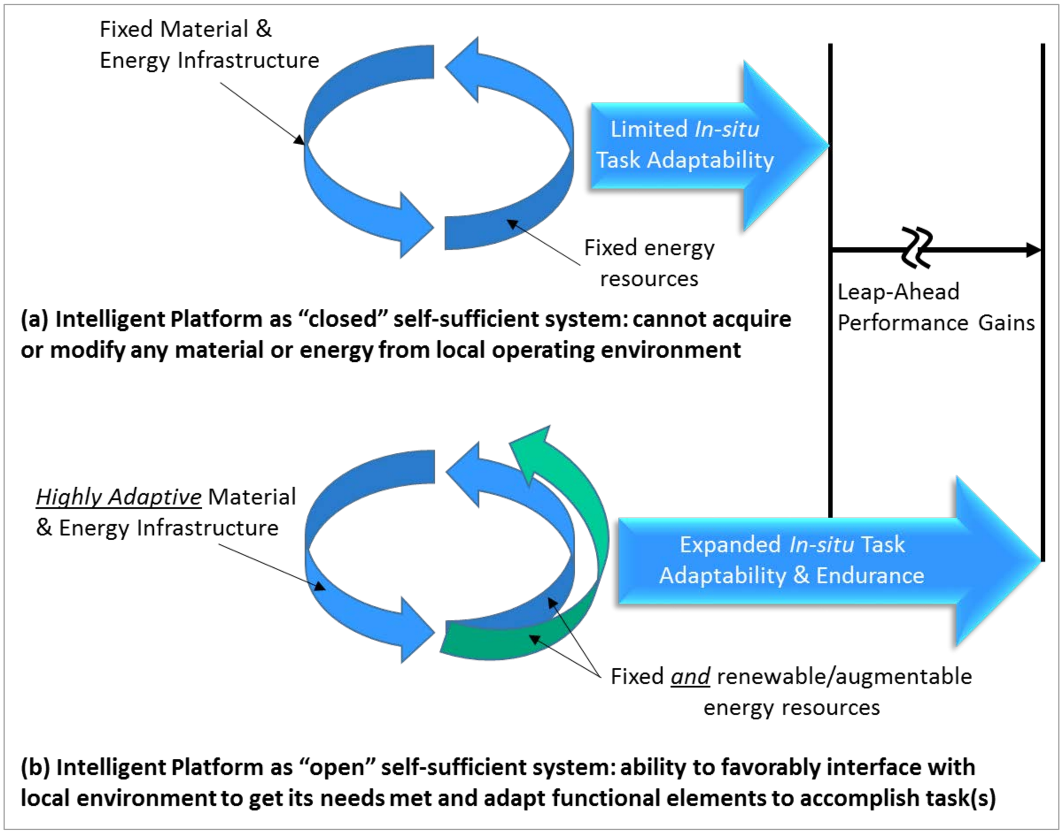

Figure 3. Aggressively, fundamentally, and comprehensively rethinking energy and power *in all aspects* of intelligent system design, operation, and mission environments

- The concept of "self-feeding robots" is attractive in the context of enabling intelligent systems for self-sustainment in austere operational environments. This notion of self-feeding robots is not new. DARPA's "EATR" program[6] for example, sponsored research in this area but the connection to materials and energy was only partially addressed, without fully identifying the gaps – and opportunities of this approach. Newer approaches, such as "synthetic metabolism" could work in meter-scale, and tens of cm- scale, but maybe not so efficiently in sub-mm scale. Technology gaps exist in enabling the "fuel" (high energy dense chemical compound) being generated from biomass by foraging. Similarly, the use of chemical/catalytic effects and electromagnetic effects for propulsion for sub-mm scale intelligent systems is very likely to be challenging for meeting the energy requirements for meter-scale device.

- Robots and intelligent systems are currently made from materials. What if they were made from a combination of materials *and* energy? What if some of the structural materials of robots could also be used as consumable energy sources – i.e., a "self-cannibalizing" robot fuselage or component? The benefits could be significant and truly unique to robotics in that the robot "platform" might continuously change its shape and structure over the duration of its mission subject to the constraint that it preserves its ability to perform its required tasks when and where needed. Such a concept would create interesting knowledge gaps to enable intelligent design and intelligent degradation of such robotic structures.

- In many current intelligent systems and platforms, the losses associated with energy conversion into usable work by the robot or intelligent system becomes significant if not limiting as the scale of these devices becomes smaller and more compact. Need to breakthrough these limitations.

- A "gradient" of chemistries could efficiently provide different responses (with different time constants). Similar, it is desirable to enable structuring of many spatially and temporally discrete phase transitions (e.g., materials jamming, enthalpy of fusion) for effective and continuous bulk response (thermodynamics and kinetics of robots)

- Explore new modes of "robotic motility" in the context of spontaneously linking mobility and actuation with energy consumption more directly. This would have broad applicability, but especially in making vastly smaller intelligent systems and robotic devices more energy efficient. Biology uses motility with great success. What are the beneficial synthetic analogs here?

- There are at least 3 length scales of intelligent systems: (a) sub-mm, (b) cm-scale (c) meter-scale. We often assume we can solve the energy technology problem by scaling. That is not quite true (currently); we cannot optimally address these three length scale categories with the same energy technology in many instances.

- Many renewable energy sources cannot alone provide the type of energy density or availability needed to power a range of intelligent systems. One approach would be to broaden the renewable energy palette – create a renewable energy portfolio and capacity for the intelligent system to harvest energy in multiple modes and from multiple sources. While advancing efficient solar energy collection materials and mechanisms should continue to be included, there are entirely different modes of harvesting energy that need to be explored. This diverse energy harvesting should be constrained by the materials and assets reliably available to the intelligent system to ensure efficiencies (e.g., the notion of *multifunctional* energy harvesting materials and mechanisms is a technology gap that could provide strategic offset gains in performance and endurance of the robots and intelligent systems). New modes of rapid biomass conversion for robots (e.g., catalysts, conversion, and process infrastructure) is but one example of another harvestable energy resource. The ability to engineer distributed chemistries to enable distributed power at point of use is consistent with these recommendations. Harvesting thermal gradients and other thermodynamic potentials occurring naturally or artificially (i.e., human-made) in the operating environment is also another mode to consider more deeply.

  - Biology paradigms could be very insightful – the robot as an organism hosted by energy resources available in the environment would define new relationships and drivers for self-sustainment.

  - Highly flexible organic materials that can withstand extreme and rapid temperature and pressure variations and maintain structural integrity could support new approaches for micro-combustion for energy efficient actuation and mobility. For example, microcombustion in elastic materials could enable storage of the kinetic energy as potential energy (in the elastic membrane or material) and allow for slower and more controlled release and use of this energy by the robot over time. It would provide efficient, direct conversion from chemical to mechanical energy and work. And the "stretchable" membrane material could contain other functionalities such as sensing, plumbing (e.g., microvalves), piezoelectric-like materials, computational and control elements, etc.

  - Although the scope of this ASPSM meeting was primarily on discrete intelligent systems (e.g., an autonomous ground or air platform) it was noted that improving material interfaces between humans and machines could significantly improve energy efficiency of robotics used in human augmentation (e.g., powered exoskeletons). There is a lot of loss due to poor adaptability of these material interfaces, and these add to the overall energy and power burden of operation (and limit duration)[7].

- **Beyond Platforms: Robots and Intelligent Systems as Continuously Evolving, Adaptive, and Self-Sustaining "Ecosystems"**

  Of all the tools conceived by humans, robots and computers are among the most unique. They are tools that have the capacity to *create their own tools*. And as they become increasingly if not exponentially capable by the confluence of an ever-broadening wave of technological advances, they will have the capacity to design tools faster and better than humans. This includes tools and "design solutions" for materials, components, and systems that may defy human intuition but optimally conform to the laws of physics. In addition, while natural, biological evolution has demonstrated breathtaking ability to aid living creatures to adapt to changing environments and needs, natural evolution is relatively slow. In theory, robots – with the aid of artificial intelligence – could evolve nearly instantly. Thus, a knowledge gap exists in moving beyond the current "fixed, as-designed" intelligent system platform to an intelligent platform that has the ability to continuously redesign and reassemble itself depending on the demands of its tasks and constraints of its environment. Instead of maneuvering with wheels or tracks or rotors (or like a snake, crab, dog, or a bird) the intelligent system could assess the optimal mode of maneuver – and then reconfigure its constituent material, structural, energy, sensing, and computational components as needed. If wheels made more sense than legs or tracks, it could create those elements from materials within itself, or from the environment, or both. In that sense, the intelligent system becomes less of a platform and more of a dynamic "intelligent ecosystem" with the ability to intelligently adapt throughout its mission and operational life cycle. Enablers for such a concept could include:

- Rapidly reprogrammable material properties using externally applied energetic fields

- Robot Circulatory systems – The notion of circulatory systems is not new in the context of robotics. However, there are new, heretofore unavailable concepts and capabilities that would warrant exploration of ideas like robot circulatory systems and "robot blood." Robot blood implies the ability to carry energy and materials throughout the intelligent ecosystem. Advances in additive and other manufacturing processes could be one of many paths to traversing these capability gaps.

- Modularity vs. heterogeneity. There are benefits to seeking breakpoints in materials and design that support reuse of components and materials, or even reconfiguration. If the mechanism is simple enough, it could serve as the basis for self-healing, or alternatively could consume self as mission progresses, shedding functionality no longer necessary. However, modularity can separate function on scales that preclude degrees of multi-functionality – risk under emphasis of system view. These concepts would give the intelligent ecosystem the flexibility it needs to adapt and respond as needed.

- Create new tools for linking intelligent ecosystem terramechanics and aeromechanics to the operational environment to deliver efficient modes of ground and air maneuver.

- *Point of use fabrication* as part of the intelligent system. A logical step beyond point of use manufacturing of components for robots by a forward deployed manufacturing capability would be to incorporate the ability to fabricate *within* the intelligent ecosystem itself. The robot contains its own mobile "factory," and like all other elements of the intelligent ecosystem, that factory (and its tools and processes) are also reconfigurable.

- If we can bring GPS and other forms of advanced information, sensing and computation into *material particles*, this opens up new ways to organize and reorganize materials in the operating environment to perform desired tasks. What's beyond "smart dust"[7] and how can it become a material resource for informing intelligent systems?

- A gap exists in the ability to realize material properties and functionalities that are tunable and assignable at the point of fabrication (stem cell analog). This includes the ability to *reassign* properties and functionalities (e.g., *low power* recycling to minimize need for new materials)

- What if the problem of navigating obstacles could be reframed entirely; what if the "obstacles" in natural and human-made environments could be resources to enable the robot or intelligent system to perform its tasks faster and for longer periods of time? Could the obstacles then be seen as assets to supply the intelligent system with energy or materials, or enable the ability to conserve energy by elastically "bouncing off" or otherwise using the obstacle in innovative ways to propel and navigate the intelligent platform around, through or over the obstacle?

- **Knowledge Gaps & Opportunities in Computation and Modeling for Intelligent Systems**

  - Advancing and implementing the use of computational and analytical tools is critical in the integrated design of materials and energy. A knowledge gap exists in enabling computation to be brought deeper and more pervasively into the materials to enable entirely new, exceptionally rapid, precise, and complex response and behaviors. Making intelligent materials and systems truly autonomous will require computation[8]. Specifically, the capability to store more than two states and perform simple logic operations[8]. This is important, as only co-locating computation with sensing and actuation can provide the scalability (with respect to the number of sensors and actuators that are integrated in the material) and robustness that make the resulting composite a *material*: unlike a system or device, a material should maintain its function when cut into any imaginable shape or when partly damaged. Approaches for how to implement such localized computation fall into two categories. One approach aims at mimicking digital logic using simple chemical or mechanical processes that activate and inhibit each other. These basic switches can then be combined into logic gates. A complementary approach is to design the composition and geometry of materials such that they subject signals passing through them to an arbitrary transfer function. Both approaches have been implemented at multiple scales, ranging from nano-scale DNA computing, to micro-scale synthetic biology, and macro-scale lab-on-a-chip like systems. Both approaches are principally Turing universal, i.e. able to perform computations of arbitrary complexity. In practice, this Turing-universality will only be of theoretical interest due to the increasing manufacturing challenges and space requirements of achieving more than a few simple logic gates or first-order dynamical systems. Hence, a knowledge gap exists in this area.

- A suite of gaps limiting the availability of desirable modeling capabilities were identified in all three breakout sessions:
  - Concurrent and holistic design of structures and materials
  - Design tools for multiphysics and multi-length scale
  - Multiscale and multiphysical optimization and design
- Coupling active learning with informing material selection and design: The idea here was to enable adaptive and robust design of robot actuation by simultaneously designing the control system with the structure. Basically, can active learning and control (through neural networks etc.) be used during the design process so that the robot's control system has some "idea" of its own design and can then adapt during its function? This may enable it to function more robustly if it breaks. During the design process various scenarios in which parts of the robot break could be simulated, and the active learning/control would have to adapt. The placement of sensors need for adaptive feedback may also be added to the optimization process.
- Multiscale and multiphysical optimization and design: Can we perform automated design and optimization of materials and structure of all

components of a robot, i.e. energy storage/generation devices, actuators, load bearing structures, and multifunctional parts[10]. The multiscale aspect would enable design of both materials and structures simultaneously, or at least small scale structures that may be helpful for multifunctional designs like structural capacitors. The multiphysics aspect would enable comprehensive design of various components, especially the design of multifunctional parts. Ideally, a comprehensive optimization algorithm would be able to design at multiple scales, and be able to use multiphysics to decide when it is appropriate to merge functionality, without intervention of a human designer deciding which components should be multifunctional *a priori*. The end goal of this concept would be a fully automated design optimization algorithm that could design the entire robot with minimal human intervention.

- In order to achieve actuation with robust performance across a wide range of operating conditions and modes, it is necessary to develop sophisticated design tools to model the multi-physics of the actuator, as well as to produce complex models for control. This is especially important for multi-functional systems which will likely have both local and global control spans.
- Actuator design through multimaterials topology design optimization: Topology Optimization (TO) could enable various novel compliant mechanical devices like force inverters, mechanical logic gates, etc.[10] Currently TO designs fully compliant mechanisms, meaning that they are made up of one contiguous structure. Can we design TO algorithms to combine discrete mechanical components along with compliant mechanisms for better performance?
- Current mathematical models are insufficient for capturing the more complex behaviors made possible by confluence of materials, computation, power, sensors, etc.
- How do we enable the integration of material and energy subsystems with inherent (and possibly highly beneficial) nonlinearities to get reliable and predictable responses and behaviors?
- The United States has maintained a decisive advantage in software programming, including interactive software and devices used in the electronic games industry. The breathtaking complexities and creativity achieved in near real-time responses between human inputs and virtual responses and graphics and interaction between human and computers

serves as a fertile model for more pervasive innovation in robotics. How, for example, could the creativity in computation, modeling, decision making, and control be brought deeper and more holistically into every aspect of materials, energy, sensing, and other elements that composes a physical intelligent system? What can be learned from academic and industrial sectors in their success at constantly stimulating innovation in software (including programming for games), and how can this be used to stimulate similar innovation and complexity in robotic devices and their behaviors? What breakthrough gains in intelligent system performance and capabilities could be made at the intersections of game and other software advances with material, energy, propulsion, computation, etc.?

- Multi-scale modelling is extremely complex when bridging just two length scales, so it is necessary to embrace some degree of modularity. The fundamental balance of efficiency versus flexibility and complexity as a function of application is difficult for a multi-function device. It is necessary to clearly articulate multi-function objective functions so that design trade-offs can be made. Additional considerations in the objective function could be graceful degradation for some failure modes, as well as highly efficient idling behaviors.
- Models for designing materials to enable behaviors for low Reynolds numbers. What bioinspiration can be modeled from insects and crustaceans?
- Modeling insight needed for materials that combine components with multiple scaling relationships so as to maintain overall system performance
- "Cyber Foam": local computation and sensing for highly and "exquisitely" engineered materials or cellular-like materials and structures to give far more significant ranges of low density mechanical response and properties than with just engineering materials alone. –Gaps exist also in consideration of the responses (e.g., extremely variability for cellular structures over very large range of sizes)
- Template Models for Scaling - How do you break classic trade-offs in actuation and motion using materials and mechanisms? E.g. through chaos and instability, through scaling and state change. Develop template models for scaling to understand how design paradigms shift as a function of size, so appropriate actuators and mechanisms can be selected based on function.

- **"Robometrology"**

It was noted that the ability to measure performance of a given system – including intelligent systems and robotics – is a powerful tool to *improve* their performance. This includes basic (6.1) research phenomena. For example, how fast is the material response *and* recovery from a mechanical load, electrical impulse, or chemical reaction? Or how much energy and time does it take for an intelligent system to perform a task – and how accurately and how reliably is that task repeatedly executed? How do we measure efficiencies in intelligent systems using multiple (and maybe simultaneous) energy sources? And how can this data be used to assess new materials and energy concepts and tradeoffs for robotics both analytically and experimentally?

There are many possible modes for an intelligent system to traverse an irregular and challenging span of terrain, including rolling, jumping, snaking, levitating, etc. Which of these is most efficient for the objective? And how is "efficient" defined? What are the measurable elements and what relationship is there between the intelligent system and the environment it interfaces with?

- Conventional measurements techniques and approaches might be adequate for elements of an intelligent system, but may be insufficient in capturing and quantifying more complex behaviors and response associated with intelligent systems. New methods for quantifying the "goodness" of robotic locomotion, propulsion, actuation, and manipulation in terms of response times and mass and energy efficiencies could be a powerful metric for assessing new concepts and tradeoffs (including new materials)
- The use of mixed modes of power generation (rather than a single energy source) might warrant rethinking the means by which the cumulative response and efficiencies of energy usage is made by an intelligent system
- How could these new robotic metrology methods be implemented into computation space for rapid assessment of "virtual" variants – to achieve more optimal solutions subject to imposed physical bounds and constraints?

- **Culture Shifts to Promote Interdisciplinary Advancement of Intelligent System Science and Technology**

In addition to identifying the knowledge gaps across the themes and thrusts of materials, synthesis, and energy for robotics and intelligent systems, the ASPSM participants felt strongly that there needs to be new modes for improving transdisciplinary research and awareness to enable these advances. This includes working across internal and external academic, industrial, and government organizations and sectors. While the emphasis of the ASPSM meeting was on identifying fundamental knowledge gaps, awareness of trends occurring externally

– and the new opportunities and knowledge gaps they create – are worthy of consideration even at the basic science level. For example, what will happen anyway in terms of technology evolution in general? What are the key advances expected in related industries that will likely be available to support the intelligent system area? As an example, while Moore's law is no more, we can still expect significant increases in processor performance with reduced power consumption, as well as the emergence of photonic integrated circuits that can support novel sensing and control systems. This might create unforeseen opportunities in many of the areas identified throughout the ASPSM discussions to address "what we can't do now and what we will need to do in the future" in intelligent systems.

Key Conclusions & Recommendations

The overarching conclusion was that, indeed, the potential performance benefits of intelligent systems and robotic devices are limited by a lack of comprehensive innovation and invention that more fundamentally addresses the *scale-appropriate energy, power, and materials* needs of these systems to deliver desired bulk responses, behaviors, and capabilities. There were many interesting and relevant research areas and thrusts identified with varying degrees of fidelity, and an attempt has been made to digest these into five Key Recommendations:

1. **Material *and* Energy Intelligence in Robotic and Autonomous Systems** – The Army needs to invest in the science of *scale-appropriate* energy and power strategies unique to intelligent systems. The ASPSM participants consistently identified physical constraints associated with current energy and power approaches as a critical limitation on intelligent system performance and potential. A holistic, comprehensive, and more deeply integrated approach to energy is recommended, and would include new research for enabling intelligent management, generation, harvesting, storage, conversion, and distributed use of energy and power. This includes introducing unprecedented levels of adaptivity so the intelligent system can develop new symbiotic and other types of energy acquisition relationships (e.g., foraging of natural and manmade materials, ambient energy harvesting) within its operating environment. It would also include the need for new concepts for materials and processes that could contain the reactive materials necessary for self-sustainment (e.g., flexible materials to contain micro-combustion, catalyst materials for synthetic metabolism to generate and consume energy-dense stored chemicals, and modes of planned material and structural degradation to enable "self-cannibalism" for extending operation under critical conditions). Research investment in these new concepts provide the underpinning science foundation for potential

agent-agent teaming of different scale intelligent systems to improve mission endurance, durability and environmental adaptability.

2. **Disrupt the Notion of an Intelligent System as a "Fixed Platform" –** The confluence of materials, synthesis, energy, sensing, and computation could provide breakthrough approaches to address current limitations to intelligent system performance, maneuver, adaptivity, endurance, and resilience. Materials and subscale functional elements could be designed to promote rapid assembly and synthesis of materials across multi-length scales, including materials that can be rapidly disassembled and decomposed so they can be repurposed based on the global and evolving needs and task demands of the intelligent system. In addition, new research is advocated to provide the intelligent system the low power ability to *create and deploy tools* to better perform its assigned tasks and enable its own self-sustainment for significant gains in operational endurance. Therefore, Army needs to invest in materials research for reconfigurable electronics and materials, distributed actuation with localized power, and computationally-driven point of need tool synthesis informed by task requirements and environmental constraints.

3. **Aggressively pursue research into Multi-Field Metamaterials –** In recent years there have been burgeoning metamaterial demonstrations, with significant successes in complex custom electromagnetic materials for optics and antennas, and early demonstrations of passive mechanical metamaterials. Advances in microfabrication, synthesis and additive manufacturing have matured to where we can start to realize complex multi-material structures. This, combined with continued progress in simulation and reduced cost computation, means it is an opportune time to pursue research in multi-field metamaterials with the goals of achieving novel materials that move us far beyond the limitations of traditional materials. For example, realizing scalable, tunable, highly-efficient actuators supporting complex articulation, with potential for integrated sense and control, as well as materials for novel platform frames, with unique mechanical, optical and electromagnetic properties. The successful realization of these broad potential materials will revolutionize autonomous platform design, performance and endurance, for example by enabling novel high density energy sources to directly drive actuation. In addition, these materials have the potential to advance broader Army system performance including in the Cyber-Electromagnetic Activities (CEMA), communications and platform arenas.

4. **Cyber Synthesis for Making Good on the Promises of Multifunctionality, Bioinspiration, and Point of Use Adaptivity –** Currently, synthesis and fabrication technologies fail to enable much richer and resilient multiscale material functionality and contiguous, defect-free morphologies and subscale structures. Such processes also fail at achieving more efficient materials interfacing for discrete device/component integration. Therefore, the Army needs to invest in exquisite manufacturing of small building blocks and infrastructure with multifunctionality and point of use adaptivity unique to intelligent systems. For example, fundamental advances in synthesis could fully enable the benefits of a "circulatory system" to support distribution of alternative high density energy and complex processing of energy at the location of consumption. The goal of this investment is to enable energy, power, actuation, and computation resource elements synthesis in a more distributed and resilient manner as needed in the global intelligent system. The benefits of such an investment would provide the scientific basis for informing the development of synthesis and fabrication methodologies to enable far more complex and energy efficient robotic and intelligent system capabilities, responses, and behaviors.

5. **Pioneering Opportunities for Computation and Modeling in Intelligent Systems** - New modes of embedded computation and sensing will be equally critical to enriching the potential of material and energy performance in intelligent systems. Recent and disruptive advances in theoretical and computational material and energy frameworks, including "materials by design," and materials that can provide logic functions and sensing can enable "state machines" and disruptively shrink the response time and enable efficient new behaviors for maneuver and actuation by distributing control *within* the materials themselves. Similarly, advancing the development of artificial intelligence as a tool to assess constraints and stretch the solution space for intelligent system design of materials, structures, processes, and energy and power cycles could enable leap ahead performance gains in mass, volume, and energy efficiencies.

Summary

Intelligent systems and robotics are critical technologies both from a strategic U.S. military perspective, as well as ensuring a healthy, globally competitive U.S. workforce and industrial manufacturing base. In sifting through the extensive output from the two days' worth of brainstorming activities, it was apparent how diverse the ideas and insights were, thanks to the equally diverse set of pioneers invited from around the country who helped generate these outcomes. There was pervasive evidence and confirmation that there are serious knowledge gaps and limits on (if not outright neglect of) concepts in energy, materials, and synthesis in the context of robotics and intelligent systems. This includes illuminating knowledge gaps for conducting enabling research at the intersections of disparate research disciplines. The spirit of the ASPSM meeting can best be summarized in one notable outcome from one of the breakout groups. This breakout group first worked together to define the current state-of-the-art in robotics and intelligent systems, followed by concepts and recommendations for unconventional innovation beyond state of the art. This particular group used the playful colloquialism “Couch Warrior” to describe the remote operation and control of some robotic platforms by Soldiers. Their recommendation for improving the performance of Couch Warriors?

Build a better couch. As humorous and glib as this suggestion is, it is a good metaphor for how the “Materials for Sustainable and Mission Flexible Intelligent Systems” ASPSM meeting *put all ideas, relationships, and aspects in play* so that more comprehensive approaches to materials, energy, synthesis, and computation could broaden the mass, volume, and energy efficient solution space for robotics in the future.

References

Note: The motivation for including any type of reference for this ASPSM Summary Report was simply to acknowledge specific items that emerged from the meeting itself, and to provide some reference or augmentation to terms and concepts that informed insights and outcomes from the ASPSM meeting. Thus, it is not intended to be an exhaustive literature survey.

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Distributed Information Processing and Data Analytics

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Adelphi Laboratory Center MD

Organizer: Dr. Tien Pham (ARL/SEDD) and Dr. Alex Kott (ARL/CISD)

Vision: The Army seeks to understand and exploit the proliferation of "big data" gathered by military assets, non-military sensors everywhere, the Internet of Things, and social media sites. The sheer volume of this information must be distilled from overwhelming levels anticipated to useful and actionable levels using a suite of trustworthy, secure, interconnected systems and techniques using machine learning and artificial intelligence.

Objective and Scope:

The main goal of this ASPSM workshop was to understand near-term and far-term implications of "big data", including but not limited to intelligence analysis requirements from key stakeholders and experts, and discuss how to address these requirements via R&D in big data processing and analytics. Thus, the ASPSM topic aimed at novel capabilities and approaches to address the big data challenges faced by the warfighters and decision makers at multiple echelons.

Focus Areas:

Topics included, but were not limited to, the following: deep learning and deep data analytics, integrated multi-modal information fusion and analytics, social sensing and social computing, smart sensing and processing and edge computing platforms, devices and services, context-aware information management and resource allocation, adaptive distributed data services and scalable and secure information infrastructures, and human information interaction (visual analytics, HMI).

Background:

The proliferation of "big data" gathered by military assets, non-military sensors everywhere (e.g., security cameras, mobile phones), the Internet of Things, and social media sites (e.g., blogs, Twitter, Facebook) poses new technical and operational challenges, threats and opportunities for the Army. The volume, diversity, density, velocity, mobility and degree of distribution of the data will be potentially multiple orders of magnitude greater than in today's world. Decision makers at every echelon need to be able to discover, collect, process and make sense of the available relevant data for situation understanding and decision-making. In order to support the future mission needs of an agile expeditionary force operating in complex dynamic environments, the Army must modernize its intelligence gathering, processing and analysis capabilities. Entirely new, currently unavailable and un-imagined techniques and tactics may become available to both friendly and adversary forces.

Gaps and Recommendations:

Exploiting Recent Advancement in Artificial Intelligence and Machine Learning (AI and ML)

With the dramatic, continuing increase in digital data generated from sensors (physical, electronic, and social) and the continuing growth in computing power (both realized and on the near horizon) the Army is at a scientific inflection point for the development of game-changing capabilities. Of particular interest is the development of portable artificial intelligence capabilities (AI in My Pocket). These technologies will produce a new culture by bringing small-scale systems to the front line for on-the-fly machine learning and then provide customized, rapid training to soldiers on what is learned. Such systems could significantly reduce the time it takes units to come up to speed as they learn the lay of new lands and cultures. The development of such a capability will require many scientific breakthroughs and discoveries. On the technological side, these pocket sized systems will need to be developed with sufficient computing, memory, and storage power to function on their own as well as part of the network to leverage the power of nearby devices in forming a processing cluster. On the scientific side, research must be performed to exploit the extent to which AI can replicate, compliment, and improve the human brain for information processing, sense making, and decision-making. Ultimately, such advancements can provide soldiers with near instantaneous knowledge to make near-immediate sense of complex environments and situations.

In addition to the science and technology developments of artificial intelligence and machine learning for the physical world, such advancements are equally, if not more pressingly, necessary in the cyber world. In this domain, AI and ML advancements are necessary to penetrate and learn an enemy's AI systems, to exploit their AI, to improve our AI, and to protect our AI. Important scientific problems yet to be solved in this space include the ability for one AI system to learn from another; the ability for an AI to validate that another AI is behaving as expected and not working outside its parameters; and the ability for an AI system to move without detection for stealth penetration and learning.

Vulnerability and Adversarial Effects in Data, Analytics Tools, and Training

Novel approaches are particularly required in ill-structured problems characterized by complexity, emergent and inconsistent behaviors, ambiguous cause and effect, and highly dynamic environments and behaviors. However, these are precisely the areas where modern AI and Machine Learning approaches are least developed, and where opportunities for adversarial deception of the machine processing are most plentiful. This is further complicated by the fact that no machine reasoning occurs without interaction with humans (users, developers, maintainers, etc.). These phenomena in human-machine systems are also notoriously difficult to understand, predict and mitigate. Approaches are needed to make machine learning and reasoning more resilient and resistant to deception, false facts, biases and influences. It might be possible that exploiting a high degree of connectivity within the future battlefield, heavily saturated with sensors and intelligent machines/munitions, will provide opportunities for cross-validation of facts and inferences. Approaches are also needed to ensure that conclusions, indicators and warnings provided by intelligent data processors are consistent with human decision-making needs and are not counter-productive with respect to human cognitive processes. Novel methods for validation and verification will need to emerge to ensure adequate quality of operations in such complex human-machine systems in the environments with such ill-structured, dynamic and deceptive problems.

Exploitation of OSINT and Non-traditional sources

The amount of easily accessible “free” information has grown exponentially with the proliferation of social media sites and apps. The use of open-source intelligence (OSINT) is not just a good idea, but a necessity for national security. Traditional OSINT sources include but are not limited to social media such as podcasts, YouTube, Facebook, Twitter; news sources; scientific articles; government documents such as patents and disclosures; mass transit maps and schedules; and the dark web. Non-traditional OSINT sources can include data about city infrastructure such as power usage, emergency responders, and hospital activity; cameras; traffic patterns; mobile phone usage; and from the human terrain information about culture, norms, teams, organizational structures, and power structures.

The primary challenges and opportunities in this space include (1) developing a means to usefully store the volume of data, discerning what to keep and what to delete, and making parts, if not all, of it portable and field ready; (2) accurately identifying the signal amongst the noise in the massive amount of information; and (3) data fusion to intelligently bring together various sources and types of data such as text, image, audio, video, sensor, AI, time, location, and person as well as combining OSINT with HUMINT and other intelligence information. Additional challenges and opportunities include not only tracking but predicting information propagation; machine learning to make sense of OSINT; identification of unknown unknowns and novel activities before they become damaging events; and the mapping of human networks with name/identity (dis)aggregation for accurate modeling.

To increase confidence in an OSINT system, analysts must develop a sense of trust in how data are collected, entered, stored, accessed, and analyzed in the system. To assist in trust-building, data must be vetted with regard to its accuracy. Additionally, the system must be able to maintain provenance information so that analysts can always trace information to its source, determine who entered it into the system, and see who accessed it along the way. Moreover, trust in the use of OSIST not automatic, but will be developed through consistent demonstration and improvement of the exploitation of these data. Such exploitation will include the use of social network analysis for social influence prediction and prevention; cross-cueing to focus attention on where to look; successful data fusion and validation; correctly identifying the signals amongst the noise; dynamic constraint-based query abilities; on-the-fly machine learning capabilities to develop common ground and ad hoc questioning; and lastly, moving from analysis of past events to prediction.

Recognizing Emergent Phenomenon and Pattern of Life sooner than Human Analysts

The implications of the operational environment in 2030 from recent TRADOC studies are contested domains and degraded operations, lethal battlefield, complex terrain and challenged deterrence. In the near future, dense urban areas or megacities will be an operational environment. Can machine learning approaches, algorithms and systems help make sense of complex situations, recognize emergent phenomenon faster than any single or group of analysts/soldiers could, and importantly, overcome confirmation bias?

The analysts and soldiers are predominately dealing with ill-structured problems which are highly unpredictable and have: (1) emergent behaviors and (2) complex relationships with freedom of action and interaction, ambiguous cause and effect, inconsistent behavior, and uncertainty. Can machine learning potentially detect and identify key features to make sense of complex relationships? Current Intelligence Preparation of the Battlefield (IPB)[*] will not be effective against emerging phenomena in which complex entities and patterns arise through interactions among simple entities that themselves do not exhibit such properties. Can computer-driven intelligence agents be used to analyze and predict emergent

[*] IPB is the systematic process of analyzing the mission variables of enemy, terrain, weather, and civil considerations in an area of interest to determine their effect on operations).

phenomena? Lastly, a risk with data mining and/or pattern analysis conducted by human intelligence analysts is that the human becomes motivated to "discover" patterns that are either meaningless or simply not there. Can machine learning systems add significantly to the analytic rigor since it looks at all the data and not just the data it believes to be relevant or able to explore a greater number of hypotheses, many of which might escaped human attention?

Infrastructure, Methods, Standards, Tools to Make Advanced Analytics Rapidly, Reflectively and Deployable

Research to make relevant advancements in big data processing and analytics and to rapidly transition analytics technology to the end users (analysts or warfighters), flexible infrastructure environments with sufficient diversity is needed to accommodate a variety of applications, domains and users. However, there are a number of challenges associated with developing a flexible data analytics infrastructure: (1) standardization of data and ground truths, analytic algorithms, software tools, performance metrics, and validations; (2) physical infrastructure that scales in terms of processing/computer power and classification levels; (3) operating infrastructure in terms of format/primitives, training and testing environment (batch or streaming); (4) validation and verification of CONOPS/doctrines at different classification levels on adaptive learning and evolving complex systems. At the minimum, the infrastructure should create a highly collaborative environment with non-propriety open architecture system, relevant data sets with ground truths, provide access to operational and domain experts and scalable computational resources, and enable experimentation for research validation and technology transition. A side benefit to having access to such an infrastructure facility is the education and training of future data scientists.

Conclusion:

The development of distributed information processing and data analytics technologies and techniques has the potential for significant payoff in future Army systems. Harnessing advances in artificial intelligence and machine learning will provide tomorrow's soldier with the tools to extract critical information from the otherwise overwhelming deluge of information on the battlefield. Focusing this research on the key Army issues will leverage commercial advances and accelerate system development, with the strong potential for leap ahead capability

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List of Symbols, Abbreviations, and Acronyms

AI	artificial intelligence
ALC	Adelphi Laboratory Center
ANN	artificial neural network
ARL	US Army Research Laboratory
ASA(ALT)	Assistant Secretary of the Army for Acquisition, Logistics, and Technology
ASPSM	Army Science Planning and Strategy Meeting
CEMA	Cyber-Electromagnetic Activities
CRA	collaborative research alliance
CSD	critical slowing down
DDDAS	dynamic data driven applications systems
DOD	Department of Defense
DSB	Defense Science Board
EEG	electroencephalogram
ERA	essential research area
GPU	graphical processing unit
HMM	Hidden Markov Modeling
HUMINT	human intelligence
IPB	Intelligence Preparation of the Battlefield
IPL	inverse power law
KB	knowledge base
ML	machine learning
NIST	National Institute of Standards and Technology
NRL	US Naval Research Laboratory
OSINT	open-source intelligence
PDF	probability density function

PHD	Probability Hypothesis Density
R&D	research and development
RG	renormalization group
RGT	renormalization group theory
SOA	state-of-the-art
SWAP	size, weight, and power

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